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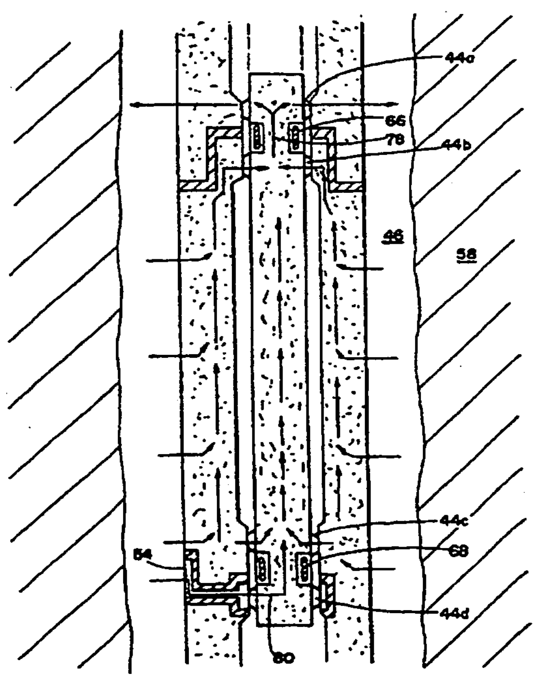
(54) Abstract Title
Retrievable resistivity tool for measurement while drilling

(57) A retrievable resistivity logging system is provided for obtaining directional resistivity information while drilling. The logging system comprises passive transmitter (36) and receiver electrodes (54) built into subs that are incorporated into the drillstring, and a retrievable instrument cartridge (22) that comprises spring loaded contacts (44) that engage contact surfaces in the subs to connect the electrodes (54, 36) to the cartridge (22). A plurality of receiver electrodes may be employed to provide simultaneous directional resistivity information from several directions around the wellbore, which may be used for detecting the presence of a nearby contrasting formation.



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(54) Title: RETRIEVABLE RESISTIVITY TOOL FOR MEASUREMENT WHILE DRILLING

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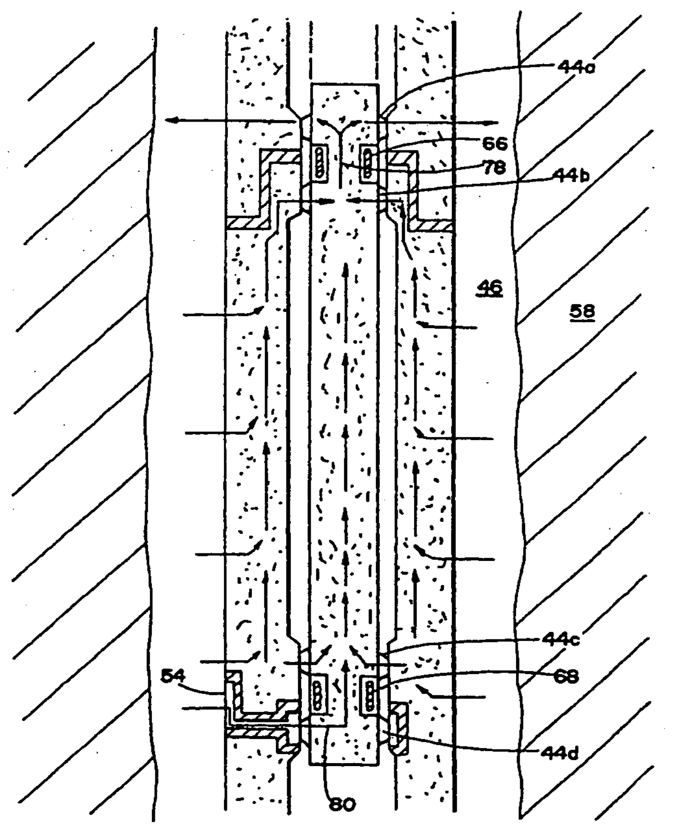

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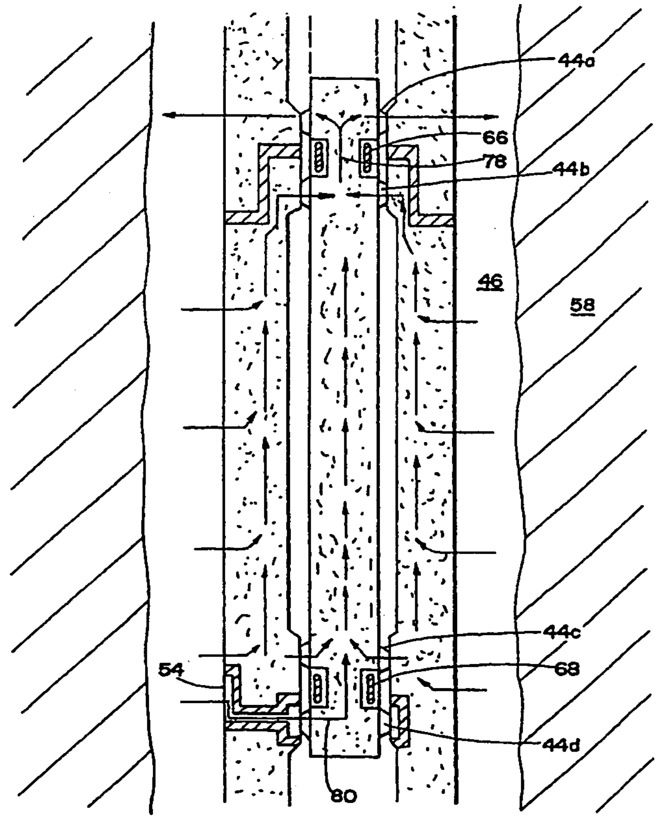

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Retrievable Resistivity Tool For Measurement While Drilling

FIELD OF THE INVENTION

This invention relates to the field of well logging, particularly for oil and gas development and exploration. More particularly, the invention provides a resistivity measuring apparatus (including a retrievable instrument cartridge) and method that is useful in measurement-while-drilling (MWD) operations.

BACKGROUND

It is well known that measurements of resistivity of subsurface formations provide useful information to engineers and geologists engaged in hydrocarbon exploration and production and other fields, such as mining. Resistivity logging is well-known in the industry. In some cases, it is performed by inducing a current to flow in the formation (and other conductive materials proximate the logging tools) and then selectively measuring the current distribution. Open-hole resistivity logging is a well-developed art, wherein the drill pipe and bit are removed from a well being drilled, and an open-hole resistivity logging tool is lowered into the wellbore and used to obtain the desired information.

Furthermore, measurement-while-drilling (MWD, also known as logging-while-drilling) systems have been developed, whereby resistivity measurements may be obtained while the drill pipe is in the hole. MWD systems permit log information, such as resistivity, to be measured in a geologic formation very soon after the formation is penetrated by the drill bit. This provides substantially "real-time" information that (a) is obtained before the formation is substantially altered by inflow of drilling fluids or other factors, and (b) may be used by the driller to control the drilling operation, for example by steering the bit so as to penetrate (or so as not to penetrate) a selected formation, which can be detected by the logging apparatus. These systems typically include transmitters and sensors disposed in or on sections of drill pipe that are located near the drill bit.

A drillstring typically comprises a bit, drill collars, and drill pipe. The lowest part of the drillstring is made up of collars. The collars are heavy walled pipe that provide weight on the bit and strength to resist buckling under their own weight. The drill pipe is thinner walled, and it is kept in tension to prevent buckling. The collars may have radial projections called stabilizers. Short drill collars, which may be adapted for specialized functions, are called "subs," and references herein to drill collars are intended to include associated subs, depending on the context of the reference, as will be appreciated by those skilled in the art.

In some prior art MWD systems, for example as described in U.S. Patent 5,235,285, a toroidal transmitting transformer is built into a drill collar and it creates a current field that flows through the drillstring and the formation. Sensors, which may be in the form of buttons, rings, or toroids, are mounted in the collar and positioned to measure the magnitude of the induced current field at selected locations. The electronic components that control the transmitter and that process the received signals are located in an annular chassis that is located within the drill collar, such that the entire instrument is contained within one piece of collar pipe, which includes a continuous annular channel to allow the drilling mud to flow through it. The system includes means for communicating the collected information to the surface. Several types of communication systems are well known in the art, including use of electrical or acoustic signals that are transmitted from a downhole transmitter to a receiver at the surface, and use of memory storage systems to record the data within the tool for retrieval when the tool is brought to the surface.

There are several problems associated with the described arrangement: (a) The system is complex, expensive and unwieldy, because all of the electronics and sensors are built into a piece of pipe that must be stout enough to support the weight placed on the bit; (b) the entire collar must be handled in order to repair any part of the system; and (c) if anything goes wrong with the system, the entire drillstring must be pulled out of the hole to gain access to it.

In U.S. Patent 4,786,874, which is incorporated herein by reference, a different sort of MWD resistivity tool is described, wherein a pair of electrodes are positioned in an insulated jacket that is formed on the outside surface of a drill collar. Both electrodes are axially positioned on the same side of the collar, and they provide a directional resistivity measurement that can be used to indicate, while drilling, that the bit is approaching a boundary between high- and low-resistivity formations. The components of this system are contained in a drill collar, and an adequate annular fluid flow path is maintained to allow drilling mud to flow through the tool. This system suffers from the same deficiencies as the system discussed above, plus problems associated with the insulated jacket, which is likely to be made of a relatively soft material. The jacket, and the electrodes it supports, are exposed to hostile wellbore conditions during drilling and are likely to be severely eroded and damaged both by contact with the wellbore walls and by the flow of abrasive mud and cuttings up past the tool.

Some prior art systems have employed a cartridge or cartridge 42 is placed inside of the drilling pipe near the drill bit, the cartridge containing the electronic circuitry or instrumentation for the logging tool, or providing electrical connection between downhole components and surface equipment. The drill bit and portions of the down-hole assembly, which may be insulated, may serve as the logging electrodes. Spring contacts or brushes are typically used to provide electrical

connections between such electrodes and the circuitry contained in the cartridge. In some systems, the cartridge is connected to the surface equipment by conductors, typically contained in an armored cable. See U.S. Patents 2,596,390 and 2,650,067 (reel for cable at surface rotates with drill pipe), which are incorporated herein by reference. In other systems, the cartridge is positioned in the drillstring near the bit, and the collected data is transmitted to the surface by wireless means, such as by electrical signals (U.S. Patent 2,364,957), by acoustic signals (U.S. Patent 4,553,097) or by storing the data until the cartridge is retrieved from the wellbore (U.S. Patent 3,293,542) (all referenced patents being incorporated herein by reference).

SUMMARY OF INVENTION

The present invention addresses the problems associated with prior MWD resistivity tools and provides an improved directional MWD resistivity tool that is relatively easy to transport, use and maintain. All of the active parts of the resistivity tool (electronics, power supply, toroidal windings, telemetry circuits, memory, etc.) are contained in a retrievable cartridge that is operatively positioned inside of a modified drill collar assembly, which comprises a drill collar, a transmitter sub, and a receiver sub. A muleshoe or other arrangement may be provided for receiving and orienting the cartridge within the drillstring in the proper position. A transmitter sub is provided that includes an insulating layer that insulates the upper or first portion of the transmitter sub, and the drillstring attached thereto, from the portion of the drillstring below insulating layer. The transmitter sub includes internal transmitter contact surfaces. The receiver sub includes an insulated directional receiver electrode and corresponding internal contact surfaces. Thus, the collar assembly is entirely passive, comprising conductive portions separated by insulating materials, the conductive portions being operably connectable to the cartridge by spring-loaded contacts or brushes in the cartridge that engage the contact surfaces of the collar assembly. An annulus is maintained between the cartridge and the collar so that drilling mud can flow through the tool and down the drillstring.

In a preferred embodiment, the customized portions of the collar assembly may be fabricated into two short subs. The upper (transmitter) sub contains the insulating layer and internal contact surfaces. The lower (receiver) sub contains the insulated, directional electrode and internal contact surfaces. One piece of conventional or customized drill collar having a selected length is positioned between the upper sub and the lower sub when the drillstring is assembled. In this way, the entire logging system (cartridge and two specialized subs) may be easily carried by a logging contractor. Alternatively, the collar and the two subs may be combined into one or more pieces of pipe having the required insulating features and contact surfaces.

The cartridge may communicate with the surface using telemetry methods known in the art, or it may store information internally for downloading when the cartridge is retrieved to the surface. The cartridge may also contain or be connected to and cooperative with other instruments, such as direction and radiation sensors and telemetry systems.

In operation, the string of drill pipe is lowered into the well, with the modified collar assembly included near the bit in the downhole assembly. At a selected time, the cartridge is lowered into place inside the drillstring using a wireline or slick line, and the line may be left in place or it may be pulled to the surface, depending on whether it is to be used for communication with the cartridge during drilling operations.

If the resistivity tool according to this invention malfunctions during drilling operations, the cartridge can be retrieved and repaired or replaced without having to pull the drillstring from the well. Because the components of this logging system that are integral to the drillstring are entirely passive it is unlikely that they will malfunction. If a wireline is used for telemetry during drilling, the cartridge can be pulled into the Kelly when it is necessary to add a joint of drill pipe without interfering with drilling operations. After the new pipe is added, the cartridge can be repositioned in the bottom-hole assembly.

In an alternative embodiment, a resistivity tool according to this invention may be provided with a plurality of directional receiver electrodes, each facing in a different direction. This enables acquisition of resistivity data from different directions around the wellbore without having to turn the drillstring as is required in the single electrode embodiment. Separate channels of receiver circuitry may be provided in the cartridge for measuring and recording the current received through each electrode, each electrode being connected to the cartridge by a separate spring-loaded contact. Methods are disclosed herein for using data obtained from a four-electrode embodiment to determine (a) the direction of a resistivity discontinuity, and (b) the apparent homogeneous resistivity of the strata surrounding the tool.

In yet another embodiment, the transmitted and received signals may be coupled between the retrievable cartridge and the transmitter and/or receiver subs using magnetic coupling techniques, wherein a transformer is formed to couple a primary winding located in a sub to a secondary winding located in the cartridge and connected to the circuitry contained therein.

Several techniques are described for electrically insulating various parts of the drillstring, including the transmitter and receiver subs, from one another, as is useful in implementing the tools described herein.

This invention therefore provides an improved system for obtaining directional resistivity data from a wellbore as it is being drilled, including an instrument cartridge that can easily be retrieved using a wireline or slick line in case of malfunction.

BRIEF DESCRIPTION OF THE FIGURES

So that the manner in which the herein described advantages and features of the present invention, as well as others which will become apparent, are attained and can be understood in detail, more particular description of the invention summarized above may be had by reference to the embodiments of the invention which are illustrated in the appended drawings, which drawings form a part of this specification.

It is noted, however, that the appended drawings illustrate only exemplary embodiments of the invention and are, therefore, not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

Figure 1 schematically illustrates a typical drilling configuration utilizing a retrievable resistivity tool according to the present invention.

Figure 2 is an elevation view of a preferred embodiment of the invention, showing typical current flow paths generated by the invention.

Figure 3 is a cross-sectional plan view of the embodiment shown in Fig. 2 on cross-section AA, showing typical current flow paths generated by the invention.

Figure 4 is a cross-sectional elevation view of the embodiment shown in Fig. 2, illustrating the structure of the transmitter and receiver subs and the contacts between the cartridge and the subs.

Figure 5 is an elevation drawing of the cartridge according to the invention, showing in partial cross section the toroidal transformers that are used for creating and detecting current flow through the cartridge body.

Figure 5a is a plan illustration through cross section BB of Fig. 6.

Figure 6 is a cross-sectional elevation view of the embodiment shown in Fig. 2, illustrating the current flow paths within the collar, subs and cartridge generated during use of the invention;

Figure 7 is a schematic illustration of the circuitry employed in a preferred embodiment of the invention.

Figure 8 is a cross sectional elevation drawing of a transmitter sub according to an alternative embodiment of the invention.

Figure 9a is a cross sectional elevation drawing of a receiver sub according to an alternative embodiment of the invention.

Figure 9b is a cross sectional plan drawing of the receiver sub of Figure 9a, through section CC.

Figure 10 is a graph showing directionally measured conductivity plotted against tool rotation angle in the presence of an adjacent conductive bed.

Figure 11 illustrates the application of a logging tool in accordance with the present invention as a dipmeter.

Fig. 12 is a longitudinal cross-sectional illustration of an instrument cartridge operatively positioned within a transmitter sub showing a magnetic coupling system between the cartridge electronics and the sub components.

Fig. 13 is a cross-section of the embodiment shown in Fig. 12 taken along section line AA-AA'.

Fig. 14 is a cross-sectional schematic of a receiver assembly, illustrating an embodiment having a single receiver electrode and multiple spring loaded secondary cores on a retrievable cartridge.

Fig. 15 is a longitudinal cross-sectional view of a receiver sub having multiple electrodes mounted therein.

Fig. 16a is a close-up cross-sectional illustration of the primary transformer cores mounted in a receiver sub and the secondary cores positioned to engage the primary cores.

Fig. 16b is a transverse cross-sectional view across the structure shown in Fig. 16a.

Fig. 17 is a close-up illustration of a core lamination structure according to a preferred embodiment of the invention.

Fig. 18 is a longitudinal cross-sectional illustration of a transmitter sub having insulating layers and coatings according to preferred embodiments of the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Referring to Figure 1, a drilling operation typically employs drilling rig 10 to cut a borehole 12 into the earth, penetrating the various geological formations that may be present. The drilling rig is adapted to turn a drilling bit 14, which cuts through the rock at the bottom of borehole 12. Sometimes this is accomplished by attaching bit 14 to the lower end of drillstring 16 and turning drillstring 16 with powered equipment at the surface. Alternatively, as shown in Fig. 1, drill bit 14 may be driven by a down hole mud motor 18 through bent sub 20. This is commonly known as a "steering tool" system, in which drillstring 16 does not rotate to turn the bit. The drillstring 16 may be turned to cooperate with bent sub 20 to steer bit 14 so as to control the direction of advance of borehole 12, thus permitting the route of the borehole 12 to be precisely steered as desired through

the subsurface geologic formations. In any event, the lower portion of the drillstring 16 is made up of heavy collars 28, which are pieces of thick-walled pipe adapted to place weight on bit 14 while keeping the upper portion of drillstring 16 in tension.

In preferred embodiments of the present invention, a resistivity logging tool 22 according to the present invention is placed in the drillstring 16 as close as possible to the drill bit 14. In a steered system, the resistivity tool may be placed above mud motor 18, receiving power and returning data to the surface through a wire line cable 24 that is passed down the center of a non-rotating (or slowly rotating) drillstring 16. In a conventional system using a rotating drillstring 16, logging tool 22 may be placed just above bit 14, and a mud pulse data telemetry system, or any other selected telemetry method, may be used to return information to the surface, as is well known in the art.

The resistivity tool 22 may incorporate or be associated with directional sensors 26 to provide directional information to the driller and to assist in controlling the steering of the drill bit, as is well known in the art. Logging tool 22 may also incorporate telemetry equipment, depending on the telemetry method that is employed in a particular application.

Above the Earth's surface 30, equipment will be positioned to receive and interpret the information generated by logging tool 22 and directional sensors 26, so that the information may be collected for later analysis or used to steer wellbore 12 into the desired position, for example to maximize recovery of hydrocarbons from a selected reservoir. Telemetry receivers and related equipment may be located in a logging truck 32 located near drilling rig 10. A data display panel 34 may be provided on or near drilling rig 10 to give the driller, engineer or geologist real-time information regarding the directional progress of the hole and the resistivities of the geologic formations near resistivity logging tool 22.

Figure 2 illustrates a resistivity tool according to a preferred embodiment of the present invention located in borehole 12. Resistivity tool 22 is operatively positioned in borehole 12, typically with an annular space 46 between tool 22 and the borehole wall. Drilling mud fills annular space 46.

The outer parts of resistivity tool 22 comprise transmitter sub 36 and receiver sub 38, and a section of drill collar 40 with a carefully chosen length. In preferred embodiments, these external conductive components are fabricated from beryllium copper, which is non-magnetic yet provides excellent strength and conductivity, although other materials may be used within the scope of the invention. Transmitter sub 36 includes insulating layer 48 that divides a first or upper portion 50 of transmitter sub 36 from a lower or second portion 52. Insulating techniques that may be used to fabricate transmitter sub 36 are shown, for example, in U.S. Patent 4,496,174, which is incorporated herein by reference. Receiver sub 38 includes insulated electrode 54, which is electrically insulated

from the remainder of sub 38 and the drillstring by insulation 60. The insulating layers in receiver sub 38 may be fabricated from PEEK ® or from other suitable insulating materials known in the art. Both upper and lower subs are designed to be rugged, reliable, low cost components that have a long life in the drilling environment. The upper end of transmitter sub 36 is operatively coupled to an ordinary drill collar 56. The retrievable instrument cartridge 42 is operatively disposed interior to transmitter sub 36, collar 40 and receiver sub 38, and it is conductively connected to the first portion 50 and the second portion 52 of transmitter sub 36, and to the body of receiver sub 38, and to electrode 54. The length of the tool is related to the depth of investigation and is a matter of design choice. In presently preferred embodiments, the tool 22 is 6 to 8 feet in length, although a longer or shorter tool is within the scope of the present invention.

In operation, the resistivity tool 22 generates an electrical survey current 23 as illustrated that exits the tool above insulating layer 48, passes through surrounding rock strata 58, and returns to drill collar 40, receiver sub 38 and insulated electrode 54 that is positioned on one side of the tool. The portion of the current that is received by the electrode is sensed and quantified by electronics within the cartridge 42. That current has an inverse relationship to the rock resistivity in proximity to the electrode. The quantified electrode current information is converted to digital data and transmitted to the earth's surface by means described below.

Figure 3 illustrates the operation of a preferred embodiment of resistivity tool 22 in cross section, with a highly conductive rock stratum 62 in close proximity to tool 22, whose boundary is substantially parallel to the borehole (and tool) axis. This situation commonly arises when drilling horizontal boreholes. Figure 3 illustrates how current flows preferentially toward the conductive stratum 62, enhancing the portion of the current received by the receiver electrode 54 when the electrode faces toward the conductive rock 62. Similarly, the presence of nearby conductive strata 62 reduces the portion of the current received by electrode 54 when it faces away from the conductive rock. If the tool 22 is slowly rotated on its axis, the current received by the electrode 54 will attain a maximum and a minimum as the electrode 54 faces either toward or away from the more conductive rock 62. Thus, in combination with data from the associated directional sensors contained within the tool string, the relative location of the conductive rock stratum 62 may be determined and the drilling operation may be modified accordingly. In a horizontal well, the conductive rock 62 may be a shale cap rock overlying an oil bearing sandstone, where the purpose is to drill a borehole for a substantial distance in an oil reservoir just below the cap rock to maximize production of oil from the bore hole.

Referring to Figure 4, a retrievable resistivity tool according to the present invention may consist of four primary parts. The inner retrievable cartridge 42 contains all of the active components: the electronic circuits and data transmission circuits, along with directional sensors.

Alternatively, the directional sensors may be located in another tool disposed in the drillstring. Cartridge 42 is retrievable; it may be installed or withdrawn through the drillstring using a slick line cable or wireline attached to the upper end of the tool. A muleshoe (not shown) may be used in the drillstring to accept and orient the cartridge 42 within the collars when it is installed, as is well known in the art. Cartridge 42 may optionally be operably coupled to other instruments, indicated as 26 in the figures, that may include for example direction sensors, thermal sensors, radiation sensors, and telemetry equipment. The upper end of cartridge 42 may include any of several connectors known in the art for providing electrical or mechanical connectivity with other components.

The body of cartridge 42 is preferably fabricated from beryllium copper or stainless steel, although other materials may also be employed. In preferred embodiments, cartridge 42 is approximately 1.75 inches in diameter, which allows it to be used in most standard drillstring configurations.

Transmitter sub 36 is electrically coupled to instrument cartridge 42 via spring actuated contacts 44 disposed on the upper end of cartridge 42 that are forced into engagement with a slightly reduced inside diameter of sub 36. In the illustrated embodiment, spring contacts 44a engage the first portion 50 of transmitter sub 36 above insulating layer 48, and spring contacts 44b engage the second portion 52 of transmitter sub 36 below insulating layer 48.

Receiver sub 38 includes insulated electrode 54 and uses a similar spring contacts as are used in connection with transmitter sub 36 to conduct electrode current to cartridge 42 for subsequent amplification and detection. As is illustrated in Fig. 4, spring contacts 44c engage the internal surface of the body of receiver sub 38, and spring contacts 44d engage an internal annular contact surface 55 that is conductively connected to electrode 54 and insulated from the body of the sub by insulating layer 60. As will be discussed in detail later, current is injected into the formation through contacts 44a, with return paths through contacts 44b, 44c, and 44d. The resistivity measurement that is made is based on the proportion of the return current that arrives through receiver electrode 54 and contacts 44d.

Drilling mud flows in the annulus 64 between cartridge 42 and the subs and collar 40, so the spring contacts are designed so that they do not block more than about 20% of the annulus area, and so that they are not rendered inoperable by the abrasive drilling mud that flows past them. In preferred embodiments, the contacts may be formed as bow springs, rubber fins with conductive elements, or spring loaded copper alloy fins. Beryllium copper is a preferred material for the contacts, due to its favorable properties of hardness, strength and conductivity.

Figure 5 illustrates a preferred embodiment of cartridge 42 in more detail. In addition to contacts 44a-d, in preferred embodiments cartridge 42 comprises a transmitter toroidal magnetic

element 66 near its upper end, between contacts 44a and 44b, as well as receiver toroidal magnetic element 68 near its lower end. Referring to Fig. 5a, which shows a cross-section view of the cartridge through section A-A (Fig. 5), toroidal elements 66 and 68 each comprise a high permeability magnetic core 70 wound with a plurality of turns (typically about 100) of insulated copper wire 72 and placed in an insulated cavity around the axis of the cartridge 42. This forms an electrical transformer where the body of the cartridge 42 forms a single turn winding and the copper wire 72 is also a winding. High pressure feed-through terminals 73 connect the copper wire to electronic circuits inside cartridge 42. By this means, the very low electrical impedance of the resistivity tool outer surface (the collar and associated current sensing electrode) is transformed to a higher impedance more conveniently coupled to internal electronic circuits.

Specifically, the transmitter circuits may supply a high voltage, low current signal and the upper toroid assembly 66 will transform this signal to one with "N-times" lower voltage and "N-times" higher survey current, where "N" is the number of turns of copper wire on the toroid. Similarly, the signal intercepted by the receiver electrode 54 is a small fraction of the transmitted current at an exceedingly low voltage. Since the accurate measurement of the current received requires that there be essentially no voltage difference between the electrode and the surrounding receiver sub and collar metal, it is important that the electronic sensing circuits maintain a near zero impedance in the electrode circuit. This is best accomplished using the toroid transformer in combination with a transimpedance amplifier circuit as illustrated in the exemplary schematic of Figure 7, which is described below.

It will be appreciated that a retrievable resistivity tool 22 according to this invention may be constructed without using the toroidal elements shown in Fig. 5, instead connecting spring contacts 44a to circuitry, which may be within cartridge 42, adapted to generate survey current. Similarly, contacts 44b, 44c and 44d may be connected to circuitry that is designed to receive and measure the return current, the toroidal transformers being replaced by conventional transformers disposed within the cartridge.

Figure 5 also shows circuit chamber 74 within cartridge 42, in which the electronic circuitry, batteries, directional instruments, telemetry apparatus, and other selected components may be located. The electronic circuits are preferably constructed on long narrow printed circuit boards, using standard methods that are well known in the art. Channels 76 may be provided extending between circuit chamber 74 and one or both ends of cartridge 42 in order to provide conduits for wiring between circuit chamber 74 and other instruments and connectors in the drillstring.

Figure 6 illustrates the current flow paths that are established during operation of a preferred embodiment of the invention. When energized, the transmitter toroidal element 66 causes a current

78 to flow through the body of cartridge 42 and out from the first contact 44a through the upper portion 50 of transmitter sub 36 above insulating layer 48 and into surrounding formation 58. Most of the current flows back into the drillstring below insulating layer 48 and back through transmitter toroidal element 66 via the second and third contacts 44b and 44c, thus completing the circuit. A portion of the returning current 80 passes through insulated electrode 54 from which it passes into the cartridge body via the fourth contact 44d, through receiver toroidal element 68, and then back to the transmitter toroidal element 66 via the cartridge body, thus completing the circuit.

The output of this directional resistivity tool corresponds to the portion of the current that returns through the insulated electrode 54, which provides a directional, quantitative indication of the resistivity of geological formations proximate the electrode. The entire assembly may be rotated in the borehole by turning the drillstring in order to scan for changes in resistivity in different directions from the borehole.

In embodiments of the invention that do not employ toroidal elements to generate and measure the survey currents flowing through the body of cartridge 42, the currents flow through signal generation and measurement circuitry located within cartridge 42, which is connected directly to spring contacts 44, rather than through the body of cartridge 42.

Figure 7 illustrates exemplary circuitry that may be used to construct a preferred embodiment of the present invention. Oscillator 110 produces a sinusoidal wave at a frequency in the range 100Hz - 10KHz, and an associated power amplifier 112 boosts the signal level to one appropriate for driving a survey current out from the first portion 50 of transmitter sub 36 (or via transmitter toroid 66 as previously described). The oscillator is preferably implemented as a digital sine wave synthesizer that also generates a synchronous square wave control signal for the phase sensitive detector 114 (PSD) used in the receiver channel. Circuitry may also be included to turn the transmitter "on" and "off" at a predetermined duty cycle to conserve power, as is well known in the art, particularly for battery powered implementations.

The receiver circuitry includes a transimpedance amplifier 116 that takes as input the current from receiver electrode 54, either directly from spring contact 44d or via receiver toroidal element 68 as previously described. Transimpedance amplifier 116 presents a very low impedance at its input, and it outputs a voltage corresponding to the detected current. The output from transimpedance amplifier 116 is input to phase sensitive detector 114 (PSD) that converts this sinusoidal voltage to a filtered DC voltage, as is well known in the art. An analog-to-digital (A/D) converter 118 receives the voltage output from PSD 114 and converts said voltage to a binary number representing the amplitude of the receiver electrode current. The binary number may be subsequently stored in memory located within the cartridge 42, or transmitted to the surface via wireline or mud pulse

telemetry (as previously noted) for real time surface readout and storage of the data. Telemetry circuitry 120 may be provided in resistivity tool 22 for implementation of the selected mode of communication.

A quantitative indication of the resistivity of strata proximate the retrievable resistivity tool may be obtained using the data provided by the tool as described above. A precomputed tool gain factor, represented by the constant "K" in the following expression, allows calculation of the average rock resistivity (assuming homogeneous rock properties) from known values of transmitter voltage, V_t, and measured value of receiver current I_r:

apparent rock resistivity, $R_a = K \bullet V_t / I_r$

In Figure 7, the transimpedance amplifier is shown as having a feedback gain resistor, Rf, so the output voltage due to the input current is:

$Vr = I_r \bullet R_f / n$

An exemplary measurement system would attempt to compensate for any drift in the transmitter output (such as, for example, with temperature changes) by recording the ratio between the two voltages V_o and V_r, thus automatically correcting such drift where $V_o = n \bullet V_r$. In this case, the calculation of apparent rock resistivity may be made as follows:

$R_a = K \bullet R_f \bullet V_o / V_r \bullet n^2$

Note that R_a is now defined by constants K and n, a precision resistor value R_f, and a voltage ratio. This results in more accurate and reliable tool operation.

In the case where the rock resistivity is not homogeneous around the tool, as for example when there is an adjacent bed boundary representing a substantial discontinuity in resistivity, the apparent homogeneous resistivity value may be approximated by averaging the apparent conductivity (inverse of resistivity) values as the tool is rotated through a full 360 degrees on its own axis. For example, referring to Fig. 10, suppose that resistivity measurements are being received from the tool in the surface data recording and display equipment at a fixed rate. The tool may be slowly rotated (e.g. by turning the drillstring) so that "m" sets of data are recorded during one full rotation of the tool, as determined by the concurrent data from the directional sensors. The tool will have rotated through an angle of approximately *360/m* degrees for each measurement. Then if $R_a(x)$ is the apparent resistivity calculated for each angular position x the apparent homogeneous resistivity may be calculated as follows:

$$R_{ah} = m / \sum_{x=0}^{m} [1 / R_a(x)]$$

This quantity corresponds to the resistivity that would be measured by standard, omnidirectional resistivity logging methods, and it may be used for correlation with other resistivity information sources.

In order to obtain an accurate value for R_{ah}, m should be at least 4, and is preferably at least 8 or 10. Note that R_{ah} is the apparent resistivity of the formation proximate the tool, out to the depth of investigation of the tool, and it includes the effect of resistivity discontinuities that are present within the measured volume.

Figure 10 graphically illustrates how apparent resistivity may be determined using a directional resistivity tool in the presence of a discontinuity. Horizontal axis 130 represents the azimuthal direction of investigation when a directional measurement is obtained. Vertical axis 132 represents the measured conductivity which is the inverse of resistivity ($R_a(x)$). In the illustrated case, 8 individual measurements 134 are obtained. Due to the presence of a relatively conductive bed on one side of the tool, the plotted data exhibits a sinusoidal character, with higher conductivity measured when the directional tool faces toward the conductive bed (see 136) and lower conductivity when the tool faces away from the conductive bed (see 138). If an adequate number of samples is obtained, the apparent homogeneous conductivity 140 may be determined by averaging the individual samples. Furthermore, the azimuthal direction 142 of the conductive bed may be determined by locating the maxima 136 of the sinusoidal curve, and information concerning the distance to the conductive bed may be obtained by comparing the maxima 136 to the minima 138 of the curve.

Figure 8 shows an alternative embodiment for transmitter sub 36, wherein sub 36 comprises an isolated and electrically insulated cylindrical annular electrode 82 on the outer surface. Electrode 82 is conductively connected to an inner annular cylindrical contact surface 84 located on the inside surface of sub 36, such that instrument cartridge 42 with associated spring-loaded contacts 44 may make an effective electrical connection with electrode 82 in order to inject survey current into the surrounding formations. Electrode 82 and contact surface 84 are electrically isolated from the body of sub 36 by insulating material 86. This embodiment of provides the advantage of greatly improved mechanical strength over the embodiment shown in Figure 4, which requires a load-bearing insulating layer 48 that may be difficult to reliably manufacture. The transmitter sub 36 illustrated in Figure 8 does, however, have the disadvantage that survey current emitted by the electrode will split into two, half returning to the drillstring below transmitter sub 36 (contributing to the resistivity measurement) and half returning to the drillstring above transmitter sub 36, where it is wasted. Thus, using the transmitter sub embodiment of Fig. 8, one half of the normal signal current will be available at the receiver electrode, resulting in a reduction of the detected signal-to-noise ratio. This

is not of great concern in wireline operations or in MWD systems that generate power from a turbine downhole, since the transmitter power may simply be increased to compensate, but it may influence the design of battery-powered MWD systems.

Figures 9a and 9b show two cross sectional views of an alternative embodiment of receiver sub 38, wherein four electrodes 54a-54d are provided, instead of the single electrode 54 shown in Figure 4. In this embodiment, the plurality of spring-loaded contacts 44d on the cartridge that are connectable to the receiver electrodes 54 are electrically isolated from each other, and the internal electrode contact surface 55 is split into four segments 55a-55d (each being conductively connected to one electrode 54a-54d). Insulating layers 60a-60d surround each electrode 54a-54d, its corresponding contact surface 55a-55d, and the conductive path 57 that connects them, so that four independent and electrically isolated electrode circuits are provided to the electronic sensing circuits in instrument cartridge 42. In the illustrated embodiment, there are four electrodes 54 spaced equally around the tool 22. One of skill in the art would recognize that other configurations of receiver electrodes 54 could be utilized in accordance with this invention. In this embodiment, when cartridge 42 is placed into its operative position within subs 36, 38 and collar 40, it may be rotationally aligned such that each spring-loaded contact 44 makes contact with the appropriate electrode contact surface 55, by the mechanical systems known in the art that are used to align directional sensors in MWD systems (e.g. a muleshoe arrangement).

The multiple receiver electrode configuration provides an important advantage over the single-electrode configuration shown in Figure 4, in that four simultaneous directionally-sensitive resistivity measurements are provided that are accurately aligned in a rotational sense with the directional gravity and magnetic-field sensors that are used to sense the spatial orientation of the drill-collar. This eliminates the need to rotate the entire drill-string (as described for the configuration of Figure 4) to determine the direction of an adjacent bed boundary or to determine an apparent homogeneous resistivity value. This configuration simultaneously provides four measurements that are identical to those provided by a single-electrode tool when it is rotated to four angular positions 90 degrees part. Thus, the direction of a bed-boundary may be estimated (to within 90 degrees) by comparing the readings from the four electrodes and looking for a maximum or minimum resistivity value, depending on whether the adjacent bed is expected to be more or less resistive than the other rock surrounding the borehole. Apparent homogeneous resistivity may also be computed by combining the four readings using the formula previously described.

In implementing a multiple electrode configuration as shown in Fig. 9b, the circuitry of Fig. 7 may be modified by providing multiple input transformers, transimpedance amplifiers 116 and PSDs 114, one of each corresponding to each receiver electrode. The resulting PSD output voltages,

one for each channel, may then be digitized and transmitted to the surface or processed further within cartridge 42.

An alternate method for calculating the direction of an adjacent rock bed of contrasting resistivity is to convert the four resistivity readings obtained using the multiple electrode receiver sub of Figs. 9a and 9b into a vector representation of the survey current flow. Referring again to Figure 10, the four electrodes are labeled A, B, C, D in a clockwise rotational sense. Assume that electrode "A" is mechanically aligned with a known axis of the orientation sensors incorporated in the cartridge. If the current sensed by electrode "C" is subtracted from the current sensed by electrode "A", and similarly the current in "D" is subtracted from "B", then we may consider the resulting current differences as "X" and "Y" respectively. This process of subtraction may be achieved electronically within the cartridge circuits, using analog electronic circuits based on operational amplifiers or transformers as is well known in the art, or it may be effectively achieved digitally by subtracting the inverse of the apparent resistivities (i.e. apparent conductivities) previously calculated for each of the four electrodes, since the apparent conductivity is proportional to the electrode current. The values of "X" and "Y" now represent orthogonal vector components of the differences in survey current flow produced by the presence of an adjacent bed boundary of contrasting resistivity. These values may be positive or negative, depending on the rotational angle of orientation of the current vector relative to electrode "A", and the exact angle T between electrode A and the direction to the contrasting strata may be calculated as follows:

rotational angle, $T = \arctan(Y/X)$

Depending on the sophistication of the computing algorithms available to the user, this mathematical statement may need to be enhanced to return a value that can vary over the full -180 to + 180 degree range, by examining the sign of X and Y to add or subtract 90 degrees as necessary by methods well known to those skilled in the art. It is also advisable to ensure that the absolute values of X and Y are not below a predefined threshold level determined by intrinsic noise in the measurements to return a valid answer to T and to avoid invalid computation conditions (X=0, for example). In the case of both X and Y being below the threshold, a software "flag" may be set indicating that the rock formations surrounding the borehole appear to be substantially homogeneous, and the angle computation may be omitted or ignored.

In the method described, the rotational angle T that has been computed gives the direction of an increasing variation in the survey current. Referring to Figure 3, we see that the presence of an adjacent rock bed that is more conductive than the rock immediately surrounding the borehole

produces an increase in the survey current intercepted by a receiver electrode that is facing toward the more conductive rock bed. If the adjacent bed were less conductive than the rock around the borehole, then the electrode current in the proximate electrode is decreased. This situation is indistinguishable from the case of a more conductive bed on the opposite side of the borehole, so it is important to know in advance the relative value of the contrasting rock resistivity. Fortunately, this information is readily available in most drilling situations where steering operations are performed because resistivity logs from offset wells or other archival geological information are usually available for correlation and comparison.

An embodiment of the present invention employing a multi-electrode receiver as illustrated in Fig. 9 may be employed to determine the dip and strike angle of rock bed boundaries penetrated by the borehole during drilling. Referring to Fig. 11, a borehole 12 will typically pass through boundaries 63 between more conductive rock 62 and less conductive rock 58. For example, oil bearing reservoir rock is often less conductive than the overlying impermeable layer. As the receiver sub 38 passes non-orthogonally through boundary 63, each of the plurality of electrodes will detect changes in apparent resistivity at different distances along the borehole, dependent upon the dip and strike angles of the boundary and the directional orientation of the axis of the borehole and the logging tool. For example, Fig. 10 shows that a receiver electrode that is still within a more conductive layer will receive a higher survey current than will an electrode that has passed into the less conductive layer. The resistivity measured by each receiver electrode may be recorded as a function of distance along the borehole, and the resistivity data may then be cross-correlated and combined with position and orientation data to calculate the dip and strike angles of the bed boundary relative to true vertical and the earth's magnetic field, as will be apparent to one skilled in the art.

The resulting dip and strike data is valuable to the driller, particularly during a transition from vertical to horizontal drilling operations, because it can indicate if the boundaries of a reservoir formation have a natural slope that should be taken into consideration during horizontal geosteering drilling operations.

In some embodiments of the present invention, magnetic coupling structures, rather than electrically conductive coupling structures, may be employed advantageously between the instrument cartridge and the transmitter sub or the receiver sub or both. Instead of the spring-loaded conductive contacts that are described above, electromagnetic transformer couplers may be employed to connect electrodes placed in the transmitter and/or receiver subs to the electronic circuits contained in the centrally located retrievable cartridge 42. This provides an alternative to the toroid transformer/spring-loaded contact method, wherein spring-loaded magnetic core elements are used to couple primary and secondary windings that are in turn connected to electrodes and electronic circuits respectively.

The use of magnetic coupling elements provides a more reliable connection system that is not as adversely affected by contamination from borehole drilling muds that often contain corrosive or abrasive materials incompatible with low-resistance electrical contacts. Some muds contain a high fraction of non-conductive mineral oil that can cause electrical contacts to become separated by an insulating film. As previously described, low-resistance connections are essential to any electrode type resistivity tool, both for efficient coupling of transmitter current between the tool and surrounding rock formations, and for low-impedance loading of receiver electrodes to sense formation currents.

In the description that follows, the following terminology is used. The "transmitter sub" is the tubular component that is typically installed between drill collars and that contains an insulating layer. The receiver sub is the tubular component that is typically installed between drill collars and that contains at least one receiver electrode that is insulated from the metal body of the sub. The "cartridge" is the retrievable instrument sonde that contains the electronic circuitry which is to be coupled to the structures in the transmitter sub and the receiver sub. In the embodiments described below, signal coupling transformers are formed when the cartridge is operatively positioned with respect to the transmitter sub and the receiver sub. The portion of each transformer that is mounted in the sub is referred to as the "primary", and the portion that is mounted in the cartridge assembly is referred to as the "secondary." The secondary transformer portions are contained in mechanical structures that are spring biased outwardly from the body of the cartridge so that they are forced into contact with the primary portions when the cartridge is put in place. The details of the mechanical structures and the spring loading mechanisms are not disclosed herein, as they are well known to those skilled in the art and matters of routine design choice. Any suitable mechanism may be used in various embodiments of the invention disclosed herein.

Figure 12 illustrates a configuration of electromagnetic couplers suitable for use to connect the transmitting circuitry in the cartridge 42 to a transmitter sub 36, with a large cross-section of magnetic core material 200, 202 available to carry a high peak magnetic flux without saturating, and thus capable of coupling high power levels. This configuration is insensitive to the rotational angle at which the sub 36 is installed in the bottom hole assembly, and the rotational angle at which the cartridge 42 engages the sub 36, since this is difficult to control due to the presence of threaded joints in the collar that is positioned between the transmitter and receiver subs. Shown in Fig. 12 is a cross-sectional view of an annular magnetic primary core 202 placed in the upper portion 50 of sub 36 surrounding primary winding 206, and a plurality of engaging magnetic secondary cores 200 spring-loaded in attachment to the cartridge housing 42 so that the spring-loaded magnetic cores 200 are forced into intimate contact with the annular core 202 by springs 212 to form the magnetic circuits. Each spring-loaded magnetic secondary core 202 has an associated winding 204 of insulated copper

wire that acts as a transformer winding when the cores are operatively placed in position during installation of the retrievable cartridge inside the collar and subs. Note that primary core 202 could alternatively be positioned in the lower portion 52 of the sub body, or more preferably between the two portions of the sub body, as shown in Fig. 18. The ends of primary winding 206 are conductively connected to upper portion 50 and lower portion 52 of sub 36 at points indicated as 203 and 205 in Fig. 12.

In a preferred embodiment of the transmitting portion of the invention, the plurality of windings 204 on the spring-loaded cores 200 are electrically connected in series and driven by an alternating current, which may be a sinusoidal current, produced by transmitter power amplifier circuit (PA) 112. This permits proper operation even if one or more of the spring-loaded secondary cores 200 does not make intimate contact with the annular primary core 202, perhaps due to interference from sand particles or vibration. Such interference may break the magnetic circuit and reduce the contribution of one of the spring-loaded cores 200 to the total electromagnetic coupling effect, but the remaining cores 200 will generally provide a sufficient amount of flux coupling to provide for acceptable operation of the assembly. If the PA circuit 112 is configured to drive a constant alternating current, then the only effect of such partial coupling will be to increase slightly the reactive load on PA 112 and reduce slightly the maximum power that can be carried by the coupler. Additionally, should some of the secondary cores 200 make intermittent contact with annular core 202, due to vibration or shock transients from the drilling operation, the current-drive scheme will significantly reduce the effect of this on the amplitude of the transmitted survey current.

Referring to Fig. 13, which is a cross section of the apparatus shown in Fig. 12 along section line AA-AA', it can be seen that in the illustrated embodiment of the transmitter portion of the present invention the primary winding 206 is disposed in an annular fashion around the circumference of the central orifice 64 formed in transmitter sub 36. The ends 203, 205 of primary winding 206 are routed through primary core 202 and conductively connected to the upper portion 50 and the lower portion 52 of transmitter sub 36, which are separated by insulating layer 48. Primary core 202 is formed in the shape of a ring, having a "U" shaped cross section as shown in Fig. 12. Fig. 12 also shows the relationship of primary core 202 and primary winding 206. Fig. 13 shows an embodiment having four spring-loaded secondary cores 200, but the invention is not limited to embodiments having a particular number of secondary cores. Each secondary core 200 is spring biased outward from the center of cartridge 42 into engagement with the exposed inward facing surface of primary core 202 by springs represented as 212 in Fig. 12. The details of the mechanical construction of the tool, including the spring biasing mechanism, is beyond the scope of the present invention, and various suitable techniques are known in the art.

It is desirable to measure the effective output voltage of the transmitter so that it can be divided by the received current in order to determine the true formation resistivity. Preferably, circuitry is provided to measure the survey voltage imposed by the survey current across adjacent rock formations, or at least to measure the voltage appearing on the outer electrode surfaces of the drill-collar and associated subs, which gives a reasonable approximation. One method that may be employed is to indirectly measure the voltage across the primary winding 206 of the transformer that is connected to the electrodes (which in the illustrated embodiment are the upper portion 50 and the lower portion 52 of transmitter sub 36), by measuring the voltage across the secondary windings 204 and adjusting for the turns-ratio of the transformer. In the case where there are a plurality of secondary windings 204 each on a secondary core 200 that may or may not instantaneously couple magnetically to the primary winding 206, this method becomes a little more complex. A person skilled in the art will understand, by analysis of the magnetic and electrical circuits, that if the rock formation can be considered to have a purely resistive impedance at the frequency of interest, any uncoupled secondary windings 204 become small inductors with a purely reactive impedance, such that a measurement of the PA 112 output voltage component in-phase with the output current is a true measure of the voltage appearing across the rock formation. This is achieved by means of a phase-sensitive detector 208 that is connected to receive a current phase signal from oscillator 110 and a voltage signal from amplifier 210, and that provides an output representing the portion of the PA 112 output voltage that is in-phase with the oscillator 110 current.

Fig. 18 also shows an embodiment of a transmitter sub assembly 36, wherein the two portions of the sub are connected by a threaded coupling having insulating layer 48 to electrically isolate upper portion 50 from lower portion 52. The transmitter primary core 202 has an "E" shaped cross section in this embodiment, and the primary coil 206 occupies both of the spaces between the legs of the core.

Fig. 14 shows an embodiment of a retrievable cartridge 42 having four outwardly biased receiver secondary core elements engaging the annular primary transformer core 220 in a receiver sub. In the illustrated embodiment, receiver sub 38 has a single electrode 54 placed on one side, and a similar signal coupling transformer arrangement can be used as described above for the transmitter sub. Electrode 54 is separated from receiver sub body 38 by insulating layer 60. Annular primary coil 218 may be disposed circumferentially around the flow channel 64 within receiver sub 38 and within annular primary core 220, which may have a cross-sectional "U" shape similar to that of primary core 202 shown in Figs. 12. Spring loaded secondary cores 222 are biased outwardly into operative engagement with primary core 220. Each secondary core 222 is wrapped with a secondary coil 224. The ends 216 of primary coil 218 are conductively connected one each to the body of receiver sub 38 and to receiver electrode 54, such that any formation current that enters receiver electrode 54 passes

through primary coil 218, from which it is magnetically coupled to secondary coils 224 by magnetic cores 220 and 222. The invention is not limited by the number of outwardly biased secondary cores provided in a particular embodiment, which is a matter of design choice.

The preferred embodiment provides reliable close-coupling of primary core 220 and secondary cores 222 to ensure that low input impedance amplifier circuits 230 are appropriately coupled to the electrode 54 so that accurate signal-current measurements may be obtained. A plurality of secondary windings 224 on individual spring-loaded secondary cores 222 are employed in the illustrated embodiment, and each secondary core winding 224 is connected to a transimpedance amplifier 230 that is located within retrievable cartridge 42. The output voltages of the amplifiers 230 are summed together by summing amplifier 231, and a phase-sensitive detector (PSD) 114 selects only the component of the voltage sum that is in-phase with the transmitter current (and therefore in-phase with the current flowing in the rock formation and into the receiver electrode). By this means, the receiver electrode 54 is always loaded by a very low impedance even if some of the spring-loaded secondary cores 222 do not make intimate contact with the primary transformer core 220 in the receiver sub, and the total received current produces a proportional output voltage from the PSD.

Generally, the most disruptive kind of shock encountered during use of this system is in a transverse direction across the axis of the logging tool, which may force some of the secondary transformer cores 222 out of contact with primary transformer core 220, but at the same time others will be pushed into even tighter coupling. In practice, the whole assembly is immersed in drilling fluid during operation, which acts as a hydraulic buffer preventing the components from moving apart (or coming together) too rapidly. By including multiple sets of opposing secondary cores 222, as shown in Fig. 14, the system can tolerate most transverse shock loads that will be encountered in normal operation. The principle of the invention is not, however, limited to any particular number or arrangement of secondary cores 222.

In preferred embodiments of the invention, the transmitter and receiver transformer cores (primary and secondary) may be constructed using high-permeability nickel-iron laminations of a type manufactured by Magnetics Inc. of 796 East Butler Road, East Butler, PA 16003-0391. In preferred embodiments of the present invention, the transmitter cores 200, 202 comprise EE-2425 laminations of 0.014 inch thickness "Alloy 48" intended for high flux density, while the receiver cores 222, 224 may be made from "Permalloy 80" material for high permeability at low signal levels. Primary coils may be formed, for example, by winding copper magnet wire of diameter in the range AWG #26 to #32 on heat-resistant bobbins, insulating the formed coil with class-H moisture-resistant varnish, and installing the core laminations into the bobbins. The whole assembly may then be pressure-impregnated with an epoxy resin, leaving the active core faces exposed, so that moisture is excluded

from the core. This assembly is then installed in the sub, and connections may then be made to the electrodes. "E" shaped cores may be employed (as shown in Fig. 16a) to provide two parallel magnetic circuits for each core, further enhancing reliability.

In the case of a four-electrode receiver sub, as shown generally in Fig. 9A and 9B, a preferred embodiment uses an alternative magnetic circuit to the one that has already been described. Fig. 15 illustrates that in presently preferred embodiments the receiver sub 38 may be formed of two pieces, and upper section 232 and a lower section 234, which are connected by pipe threads 236. A space is formed between the lower end of upper section 232 and an annular shelf 238 formed on the interior surface of lower section 234. The primary receiver coils 243 and cores 242 are placed into this space before the upper section 232 and lower section 234 are joined.

As shown in Figs. 16A and 16B, which are expanded and detailed views of a preferred embodiment of a receiver transformer arrangement, two sets of circular primary "E" cores 242 are stacked on top of each other, and primary coils 243 are wound around the circumference of the interior flow channel between the legs of the "E" cores. Four primary coil windings (designated 243 A,B,C, and D) are wound around the interior circumference of receiver sub 234 between each of the legs of the "E" cores 242a and 242b, and one end of each coil 243 is connected to one of the four electrodes 246 similarly designated. The other end of each primary coil 243 is conductively attached to the body of receiver sub 234, creating a current path from each receiver electrode 246, through the corresponding primary coil 243, and then to the steel of the drill string. Each winding 243 creates magnetic flux in an individual magnetic circuit. Although any two adjacent windings share one "leg" of an "E" core 242, this does not result in significant unwanted coupling between windings.

Corresponding "E" cores may be used for the spring loaded secondary transformer cores 244A and 244B. A secondary winding 248A-D is provided around each of the secondary cores 244 between the legs of the "E" shaped secondary transformer configuration. Each secondary winding 248 is coupled to the receiver electronics in retrievable cartridge 42. In the preferred embodiment, each "E" core 242, 244 is approximately 1 inch high, so axial alignment of the spring-loaded core 244 surfaces with the primary core 242 surfaces can be readily achieved. In this arrangement, rotational alignment of the cartridge 42 with the receiver sub 38 is not necessary in order to make the appropriate connections, although a preselected alignment is normally provided by use of a muleshoe at the base of the cartridge 42.

In the illustrated embodiment, each receiver electrode (e.g. 246 D) is operatively coupled to a measurement amplifier 231 and PSD circuit 114 (see Fig. 14) in cartridge 42 through an individual primary transformer circuit (e.g. coil 243D) and several secondary spring-loaded transformer cores and windings (e.g. 248D, one of which may be provided on each of several redundant secondary core

assemblies). The advantage of using multiple parallel magnetic circuits is thus retained with only a modest increase in complexity.

This configuration of stacked core assemblies providing multiple magnetic circuits may have other uses in this or similar tools , such as the provision of separate insulated voltage-sensing electrodes on the receiver sub that may be connected to auxiliary voltage-measuring amplifier and PSD circuits (not shown) in the retrievable cartridge. Such structures provide special advantages in sensing the true survey voltage in the vicinity of the current-sensing electrodes. As is known to those skilled in the art, this more accurate measurement can enhance the accuracy of the resistivity log in cases where the borehole fluid is more resistive than the surrounding rock formations.

It should be appreciated that reliable and accurate operation of the tool according to this invention depends on close contact at the interface between the fixed (primary) and movable (secondary) magnetic cores in the transmitter and receiver portions of the device. One method to provide close contact is to use a high engagement force on the spring loaded cores to overcome any misalignment or the presence of foreign material. Another is to form a ferromagnetic "bristle" structure on the mating surfaces (not shown), whereby a modest engagement force is concentrated in a multiplicity of tiny contact points, each of which may be independently spring energized so that misalignment is compensated. This method has the additional advantage that, if the two halves of the transformer assembly are slideably engaged, the "bristles" act as cleaning brushes to scrub contaminants away from the engaging surfaces.

Yet another method, which is used in a presently preferred embodiment of the invention, is to arrange the core laminations to form a multiplicity of parallel blades that act like bristles, but that make multiple lines of contact rather than multiple points of contact. This increases the area of contact so that the cross-sectional area of the magnetic circuit is not significantly reduced, retaining a high power-transmitting ability of the transformer. An example of a preferred arrangement is shown in Figure 17, where the individual secondary laminations 256 (which may be, e.g. 0.014 inch thick) of the secondary transformer core 244 are stacked in such a way that they are alternately offset by +/- 0.010 inch. The interior facing surface formed by primary laminations 254 reflects the laminated structure sufficiently to cause the outwardly extending secondary laminations 256 to engage it such that the extending secondary laminations 256 become aligned with and in close contact with primary laminations 254. Contaminating particles 258 and liquids which may be present on the mating magnetic core surfaces when they are brought together are scraped away by the extending secondary laminations 256 and may be deposited in the spaces formed between adjacent extending secondary laminations 256, thus further enabling a close mechanical and magnetic coupling between primary laminations 254 and secondary laminations 256.

In an alternative arrangement, the primary laminations 254 may also be alternately offset (not shown), such that, when they are brought together, the alternately extending primary laminations 254 and secondary laminations 256 will tend to lock together when slideably engaged, with the blades of each fitting snugly into the grooves of the other in an interlaced manner. This arrangement can provide a total contact surface-area that is greater than the superficial surface-area of the two transformer core engaging surfaces, resulting in high transformer efficiency and further reducing the likelihood that shock or vibration can separate the cores, yet allowing disengagement when desired.

Referring to Fig. 18, transmitter sub 36 has upper portion 50 and lower portion 52, which are both formed of conductive steel, but which must be electrically insulated from one another in order to allow proper operation of the retrievable resistivity tool as described in this patent. An insulating layer 48 separates the upper portion 50 from the lower portion 52. The insulating layer may be formed as part of a threaded connection, as shown in Fig. 18, or as part of an adhesive or other non-threaded connection, as indicated in Fig. 12 or otherwise. Referring again to Fig. 18, it is also beneficial in some embodiments to provide insulating coatings on selected interior and exterior surfaces of the transmitter sub 50, to prevent conductive paths from forming and bridging insulating layer 48. Also, core insulating layers 260 may be formed as described herein (or by other means known in the art) to insulate the transformer core from the sub body (in transmitter or receiver sub), and electrode insulating layers 60 may be formed as described herein to insulate electrodes 246 from the body of receiver sub 38.

Several methods of constructing suitable electrically insulating joints and layers that are used in the transmitter and receiver subs will now be described. Other methods known in the art and hereafter developed may also be suitable for implementation of this invention. Although the applied voltages are not high, ranging up to a maximum of about one volt, the joint is subjected to enormous mechanical stresses in compression, tension, torsion, and bending moment. These stresses are repeated cyclically many millions of times during the life of the tool, under conditions of high temperature and pressure. In addition, commercial considerations require the cost to be low enough that occasional breakage and loss of these non-retrievable portions due to drilling problems (such as stuck bottom-hole-assemblies) do not impose an unacceptable financial burden. Two methods are described, based on the use of relatively thin insulating layers used to bond together two metal parts with a threaded joint and a tapered joint.

The metal surfaces where insulating layers are to be formed may be coated with extremely hard ceramic insulating materials such as aluminum oxide that are molecularly and/or mechanically bonded to the metal. Plasma spraying methods may be used to fire molten droplets of metal and ceramic at a metal substrate to provide a bonding layer, which is then covered with a layer of pure

ceramic by modifying the material mixture. This process is available as "Plasmadize" from General Magnaplate Corporation of Linden, New Jersey, and from other companies. Although quite thin layers (0.001 inch) that are very durable and non-porous can be employed, the ceramic layer can also be built up to a thickness of about 0.060 inch or more where necessary. The ceramic surface has a microscopically rough texture that enhances adhesion of another bonding material. As shown in Figure 18, two metal pieces may be joined with an insulating layer separating them by precision-machining each piece with matching threaded or tapered surfaces, which may be accurate to less than about 0.001 inch but allowing for a gap at final assembly of typically about 0.005 to 0.050 inch. The two pieces of metal are coated with ceramic over the joining surfaces and then assembled with a liquid cement material disposed between the ceramic surfaces. The cement may then be cured by a thermal process or other suitable process, which securely bonds the cement layer to the two hard-coat material surfaces. In preferred embodiments, the final thickness of cement may be about 0.003 to 0.030 inch.

The ceramic layer may also be employed to form an internal insulating coating 262 or an external insulating coating 264 on selected portions of the sub components, in order to insulate selected portions of the conductive steel sub body from the drilling fluids that they will be in contact with during drilling operations. A suitable ceramic coating will provide adequate hardness and durability to provide an insulating layer that will stand up to the abrasion and impact that the sub will be subjected to in the downhole environment.

The cement referred to above may be specially formulated with powdered filler materials so that it has a thermal coefficient of expansion (TCE) closely matched to that of the metal parts being joined, resulting in a structure that is very durable under repeated thermal cycling. A suitable epoxy cement material is Duralco 4525 made by Cotronics Corp. of Brooklyn, New York 11235, and a suitable filler material is aluminum oxide powder, which is available in various grain sizes for use as an abrasive, from Washington Mills, of North Grafton, Massachusetts, under the trade name "Duralum". This material has a TCE lower than that of stainless steel or beryllium copper, so it makes an ideal filler for combination with the cement, which generally has a higher TCE than that of the metal parts being joined. When mixed in the correct proportions, the cement compound TCE can be adjusted to match the TCE of the metal. Alternatively, a suitable ready-made cement formulation is Ceramabond 571 made by Aremco Products, Inc. of Ossining, New York 10562.

A second method of forming the required insulating layer involves replacing the cement materials with a rubber compound such as "Viton", "Aflas" or another similar elastomer that will withstand high temperatures. The elastomer can be molded in place under high pressure to eliminate voids. A tapered joint design (rather than the threaded design) may be more appropriate in this case, because a thin sheet of a raw rubber compound can be placed between the two ceramic-coated metal

parts, which may then be forced together under high pressure while being heated to soften and eventually cure the rubber. If the dimensions and the process are well-controlled, using techniques known in the art, this process provides a very strong joint with the rubber chemically bonded to the ceramic layer. The rubber layer acts as a shock-absorbing layer to prevent localized stresses from fracturing the brittle ceramic layers.

Further modifications and alternative embodiments of this invention will be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the manner of carrying out the invention. It is to be understood that the forms of the invention herein shown and described are to be taken as the presently preferred embodiments. Various changes may be made in the shape, size and arrangement of parts. For example, equivalent elements may be substituted for those illustrated and described herein, and certain features of the invention may be utilized independently of the use of other features, all as would be apparent to one skilled in the art after having the benefit of this description of the invention.

CLAIMS

I claim:

1. A resistivity logging system for use in measurement-while-drilling operations wherein the logging system is located in a down-hole assembly near a drill bit while a well is being drilled, the logging system comprising:

a drill collar having a selected length;

a transmitter sub connected to one end of the drill collar, the transmitter sub having an insulating layer that electrically isolates a first portion of the sub from a second portion of the sub, the transmitter sub having internal contact surfaces coupled to the first portion of the sub and the second portion of the sub;

a receiver sub connected to the other end of the drill collar, the receiver sub comprising a body, a receiver electrode disposed over a selected portion of its outer surface, and a receiver contact surface exposed on a selected portion of its inner surface, the receiver electrode and the receiver electrode contact surface being coupled to one another;

an instrument cartridge selectively positionable within the drill collar and subs, the cartridge having transmitter contacts that engage the internal contact surfaces on the transmitter sub, and receiver contacts that engage the receiver contact surface, the cartridge comprising current injection circuitry connected to inject current into the formation through the transmitter contacts and current sensing circuitry connected to sense the current returned through the receiver contacts.

2. The logging system of claim 1, further comprising memory located within the cartridge for storing said processed signal data.

3. The logging system of claim 1, further comprising signal processing circuitry for providing processed signal data corresponding to the magnitude of the sensed current.

4. The logging system of claim 3, wherein the signal processing circuitry comprises an analog-to-digital converter, and wherein the processed signal data is provided in a digitized format.

5. The logging system of claim 1, wherein the transmitter contacts and the internal contact surfaces coupled to the first portion of the transmitter sub and to the second portion of the transmitter sub are conductive contacts.

6. The logging system of claim 1, wherein the transmitter contacts on the cartridge and the internal contact surfaces coupled to the first portion of the transmitter sub and to the second portion of the transmitter sub are magnetic contacts comprising coils and magnetic cores.

7. The logging system of claim 1, wherein the receiver contacts and the receiver contact surfaces are conductive contacts.

8. The logging system of claim 1, wherein the receiver contacts and the receiver contact surfaces are magnetic contacts comprising coils and magnetic cores.

9. The logging system of claim 1, wherein the receiver sub comprises a plurality of receiver electrodes and corresponding receiver electrode contact surfaces.

10. The logging system of claim 1, wherein said current injection circuitry comprises a toroidal coil transmitting transformer mounted coaxially on the cartridge between the first and second contacts, the transmitting transformer having windings connected to receive a preselected transmit signal.

11. The logging system of claim 1, wherein said current sensing circuitry comprises a toroidal coil receiving transformer mounted coaxially on the cartridge between the third and fourth contacts such that current from the receiver electrode passes through the receiving transformer, the receiving transformer having windings connected to signal processing circuitry in the cartridge.

12. The logging system of claim 6, wherein the current injection circuitry comprises a current source that is connected to drive a current through secondary coils wrapped around secondary cores attached to the cartridge, and wherein the secondary cores are selectively magnetically coupled to a primary core mounted in the transmitter sub, the primary core having a primary transmitter coil associated therewith, the primary core having two ends that are connected to the first and second portions of the transmitter core respectively.

13. The logging system of claim 8, wherein the current sensing circuitry comprises one or more low impedance amplifiers connected to receive current signals from windings wrapped around secondary cores attached to the cartridge, and wherein the secondary cores are selectively

magnetically coupled to one or more primary cores mounted in the receiver sub, the primary cores having one or more primary receiver coils associated therewith, each primary receiver coil having two ends, one end of which is attached to a receiver electrode.

14. A resistivity logging system for use in a measurement while drilling operation, wherein the logging system is located in a drillstring proximate a bit, the logging system comprising:

a transmitting electrode located on an external surface of the drillstring and electrically connected to a transmitter contact surface on an internal surface of the drillstring;

a directional receiving electrode located on an external surface of the drillstring and electrically connected to a receiver contact surface on an internal surface of the drillstring; and

a retrievable instrument cartridge operably disposed within the drillstring and removably coupleable to said transmitter contact surface and to said receiver contact surface, the cartridge comprising signal generation circuitry and received current measuring circuitry.

15. The resistivity logging system of claim 14, wherein the transmitting electrode is that portion of the drillstring that is located above an insulating layer that separates a lower portion of the drillstring from an upper portion of the drillstring.

16. The resistivity logging system of claim 14, wherein the cartridge comprises a toroidal coil transmitting transformer mounted coaxially on the cartridge.

17. The resistivity logging system of claim 14, wherein the cartridge comprises a toroidal coil receiving transformer mounted coaxially on the cartridge.

18. The logging system of claim 14, wherein the logging system comprises a plurality of receiver electrodes and corresponding receiver electrode contacts.

19. The logging system of claim 14, further comprising disengagable transformer means for magnetically coupling the signal generation circuitry to the transmitting electrode, and for magnetically coupling the received current measuring circuitry to the receiving electrode.

20. The logging system of claim 14, wherein the instrument cartridge comprises a transimpedance amplifier.

21. The logging system of claim 14, wherein the instrument cartridge comprises a phase sensitive detector.

22. The logging system of claim 14, wherein the retrievable instrument cartridge comprises integrated direction sensing apparatus.

23. A resistivity logging system for use in measurement-while-drilling operations wherein the logging system is located in a drillstring near a drill bit while a well is being drilled, the logging system comprising:

transmitting electrode means incorporated into the drillstring for injecting a survey current signal into a surrounding rock formation;

directional receiving electrode means incorporated into the drillstring for receiving a return current;

a retrievable instrument cartridge operably disposed within the drillstring, the cartridge comprising:

signal generator means for generating said survey current signal and means for conducting the survey current signal to the transmitting electrode means; and

received current measuring means connectable to said directional receiving electrode means for measuring a survey current signal that returns therethrough to provide directional resistivity information.

24. The system of claim 23, further comprising direction sensing apparatus contained within said retrievable instrument cartridge.

25. The system of claim 23, further comprising means for transmitting the directional resistivity data to the surface.

26. The system of claim 25, further comprising means for displaying the directional resistivity data to an operator at the surface.

27. A transmitter sub for use in a measurement while drilling system, wherein a retrievable instrument cartridge provides a survey current for injection into rock formations proximate the transmitter sub, the transmitter sub comprising a cylindrical body having threaded connections at each end and an insulating layer electrically separating a first part of the sub from a second part of the sub, the sub having a reduced internal diameter over a portion of its length, the internal surface of the sub providing contact surfaces for communication with said instrument cartridge.

28. The transmitter sub of claim 27, further comprising a primary magnetic core and a primary winding having two ends, one end coupled to each of the first part of the sub and the second part of the sub.

29. A receiver sub for use in a measurement while drilling system, wherein a retrievable instrument cartridge provides a survey current for injection into rock formation proximate the receiver sub, the receiver sub comprising:

a generally cylindrical body having threaded connections at each end;

at least one directional receiver electrode located on an external surface of the cylindrical body sub;

a contact surface located on an internal surface of the receiver sub coupled to said directional receiver electrode; and

an insulating layer electrically separating the body of the sub from the directional receiver electrode, the receiver sub having a reduced internal diameter over a portion of its length where the contact surface is located.

30. A retrievable instrument cartridge for use in a resistivity logging system having electrodes positioned on electrode subs integrated into a drillstring, the cartridge being operatively positioned inside the drillstring proximate the electrode subs, the retrievable instrument cartridge comprising a signal generator for producing a survey current; signal processing circuitry for measuring a received portion of said survey current; first coupling means adapted to connect the signal generator to an electrode sub; and second coupling means adapted to connect the signal processing circuitry to an electrode sub.

31. The retrievable instrument cartridge of claim 30, wherein the first coupling means and second coupling means comprise spring loaded contacts that are adapted to slideably engage internal contact surfaces of the electrode subs.

32. The retrievable instrument cartridge of claim 30, wherein the signal generator comprises a toroidal coil transmitting transformer mounted coaxially on the cartridge.

33. The retrievable instrument cartridge of claim 30, wherein the signal processing circuitry comprises a toroidal coil receiving transformer mounted coaxially on the cartridge.

34. The retrievable instrument cartridge of claim 30, wherein the signal processing circuitry comprises an analog to digital converter.

35. The retrievable instrument cartridge of claim 30, wherein the signal processing circuitry comprises a transimpedance amplifier.

36. The retrievable instrument cartridge of claim 30, wherein the signal processing circuitry comprises a phase sensitive detector.

37. The retrievable instrument cartridge of claim 30, further comprising integrated direction sensing apparatus.

38. A method of detecting the proximity and direction of a resistivity discontinuity relative to a drillstring during a measurement-while-drilling operation comprising:

providing a resistivity logging tool having at least one directional current sensor located in the drillstring;

measuring the current returned through each of said at least one directional current sensor to provide directional resistivity data;

rotating said drillstring as desired to provide additional directional resistivity data; and

determining the existence and direction of said resistivity discontinuity by evaluating said directional resistivity data.

39. The method of claim 38, wherein the logging tool comprises four directional current sensors located 90 degrees apart, a first and a third current sensor being 180 degrees apart and a second and a fourth current sensor being 180 degrees apart, and wherein the evaluating step comprises:

determining a first difference (X) between the current measured by the first and third sensors;

determining a second difference (Y) between the current measured by the second and fourth sensors;

providing the angle "T" between the angular position of the first sensor and the angular position of the resistivity discontinuity by solving the equation: T = arctan (Y/X).

40. The method of claim 39, wherein the determining steps are performed using analog circuitry operating on the measured current signals.

41. The method of claim 39, further comprising digitizing the measured current signals received from each of the directional current sensors to provide digital data, and performing the providing step using the digital data.

42. A method of determining the average homogeneous resistivity of a rock formation using a directional resistivity logging tool, the method comprising:

obtaining a plurality of directional resistivity measurements $R_a(x)$ by rotating the logging tool through 360 degrees while measuring directional resistivity at *m* uniform intervals;

using a digital computer to solve the equation

$$Rah = m / \sum_{x=0}^{m} [1 / Ra(x)]$$

to provide Rah, which is the average homogeneous resistivity of the surrounding formations.

43. A method of determining, while a wellbore is being drilled, the dip and strike angles of a geologic boundary through which the wellbore passes, the method comprising

providing near a drill bit a resistivity logging tool having a plurality of directional receiver electrodes disposed on an outer surface of a drill collar, each receiver electrode being operably connected to a current detection circuit, each of said current detection circuits being connected to a digital processor; and providing direction sensing apparatus proximate said receiver electrodes;

generating a survey current using said resistivity logging tool;

receiving a return current signal through each of said directional receiver electrodes;

quantifying each of said return current signals using the current detection circuits to provide directional current data;

acquiring directional orientation data using said direction sensing apparatus substantially simultaneously with receiving the return current signals; and

processing said directional current data and directional orientation data using said digital processor to determine the dip and strike angles.

44. The method of claim 43, further comprising providing a retrievable instrument cartridge containing said current detection circuits, and placing said retrievable instrument cartridge internal to the drill collar proximate said receiver electrodes such that the current detection circuits are operably connected to said receiver electrodes.

45. The method of claim 44, wherein the providing step comprises providing said direction sensing apparatus within said retrievable instrument cartridge.

46. A method for forming an insulated instrument sub for use in a drill string having a first portion and a second portion electrically insulated from the first portion, comprising forming mating surfaces on each of the first and second portions, coating each mating surface with a ceramic material, joining the ceramic coated mating surfaces in their operative relationship with an adhesive material disposed between them, and curing the adhesive material to effect a permanent insulated assembly.

47. The method of claim 46, wherein the coating step comprises first applying a bonding layer to the mating surfaces and then applying a ceramic layer on top of the bonding layer.

48. The method of claim 46, wherein the adhesive material is an adhesive cement combined with a powdered filler material that has a coefficient of thermal expansion similar to that of the first and second portions of the instrument sub.

49. The method of claim 46, wherein the adhesive material is a rubber compound.

50. An apparatus for coupling a signal between an electrode mounted in a drill collar sub and circuitry in an instrument cartridge, the drill collar sub having a flow channel formed therein, comprising:

a first winding encircling the flow channel, one end of the first winding being connected to the electrode;

a first core made of magnetically permeable material encircling the flow channel and operatively associated with the first winding and having legs exposed to the flow channel;

a second core made of magnetically permeable material mounted in an outwardly biased manner on the instrument cartridge and adapted to engage the first core to form a complete transformer core; and

a second winding wrapped around the second core, the second winding carrying a signal that is proportional to the signal conveyed by the electrode and conducted through the first winding.

51. The apparatus of claim 50, further comprising a plurality of second cores and associated windings, each second core being adapted to operatively engage the first core at a different radial location, each second core having a second winding wrapped around it.

52. The apparatus of claim 50, further comprising:

a plurality of first windings encircling the flow channel, each first winding spaced along an axis of the sub from the other first windings; and

a plurality of second windings wrapped around the second core, each second winding corresponding to one of the plurality of first windings;

wherein the first and second cores are stacked cores adapted to form an independent magnetic circuits coupling each set of corresponding first and second windings.

53. The apparatus of claim 50, wherein at least one of the first core and the second core comprises a stack of laminated plates of high permeability magnetic material arranged to form an engagement surface exposing a lateral edge of each of the laminated plates, and wherein the plates are positioned such that the lateral edges of selected plates are offset from the lateral edges of neighboring plates.

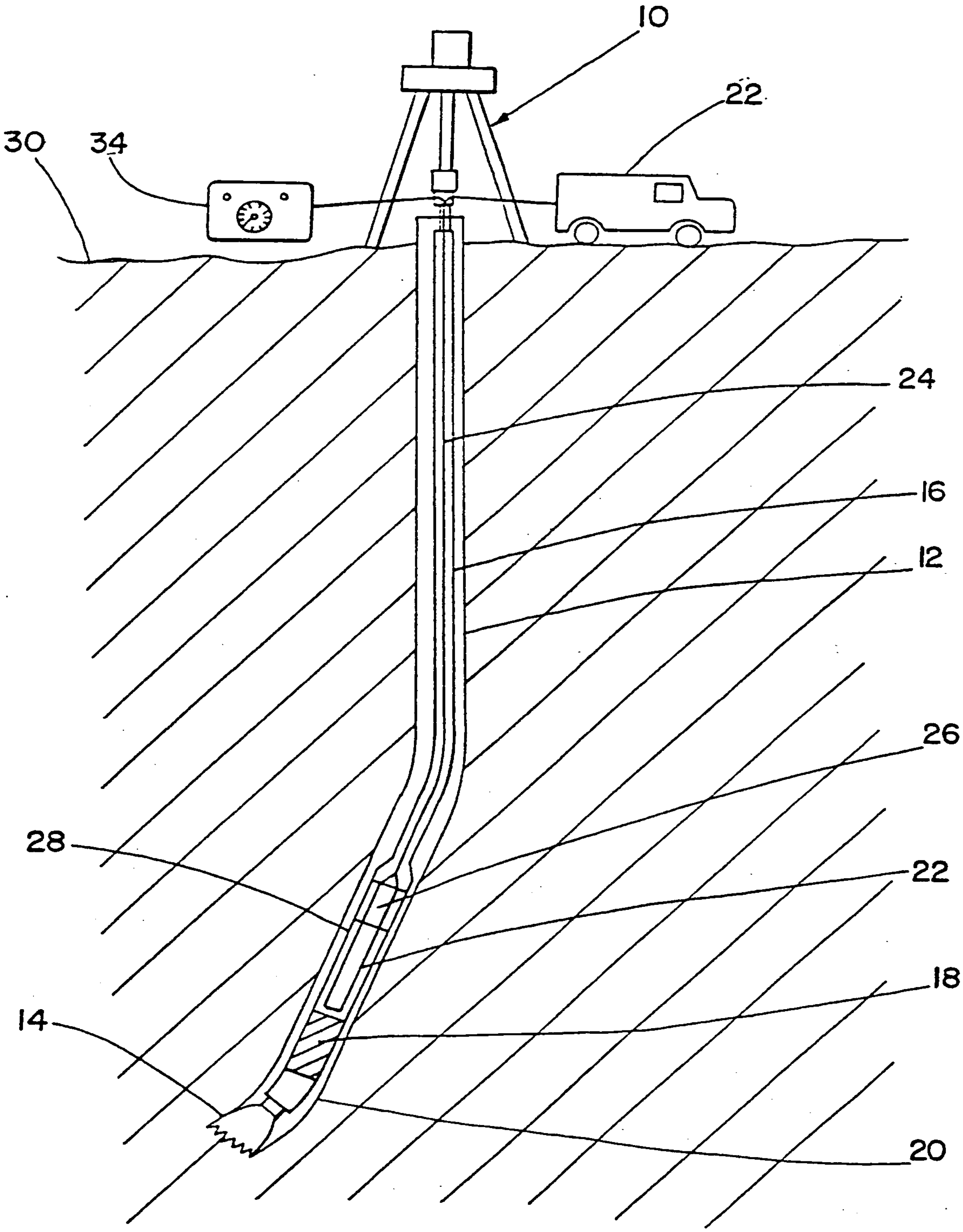


Fig. 1

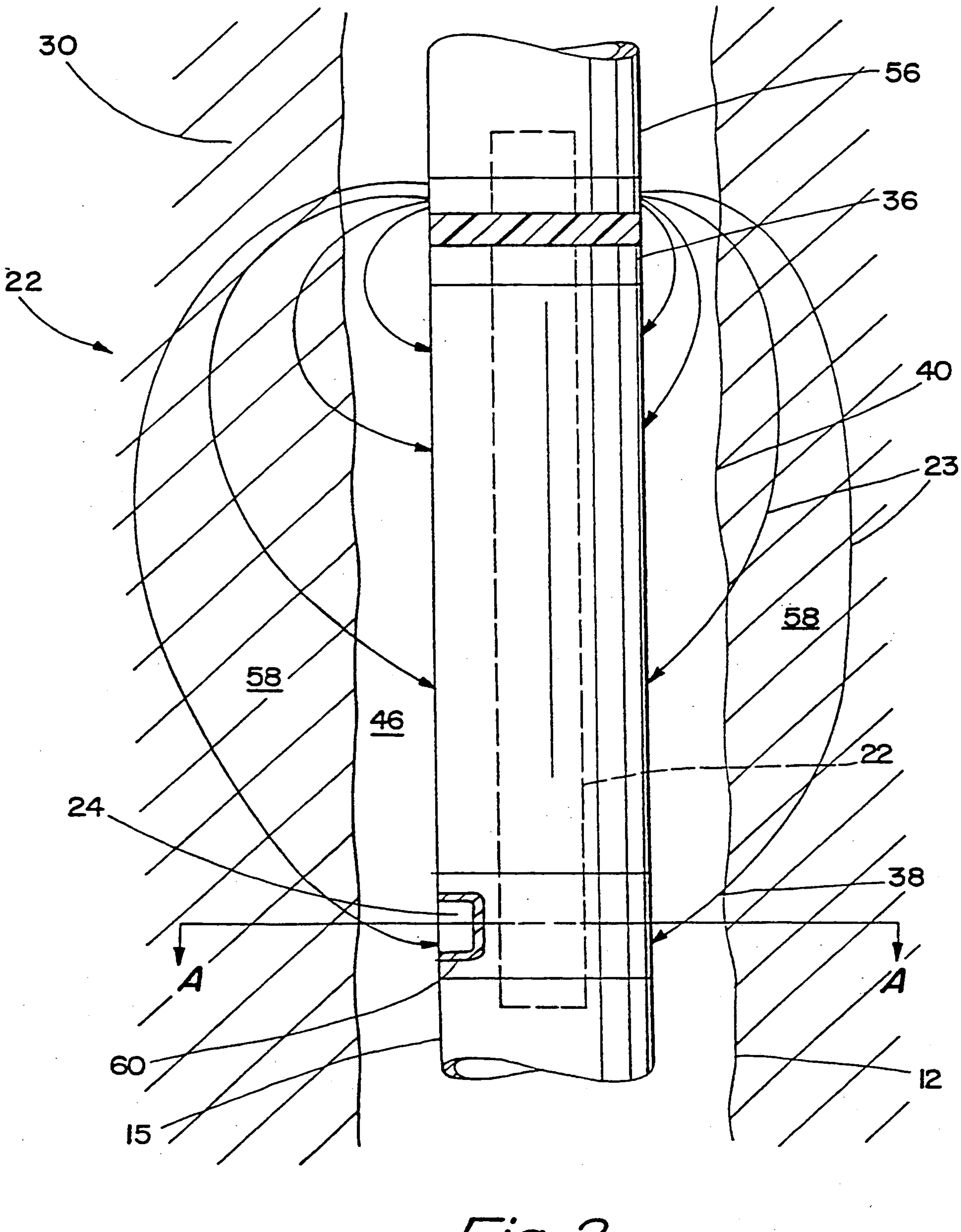


Fig. 2

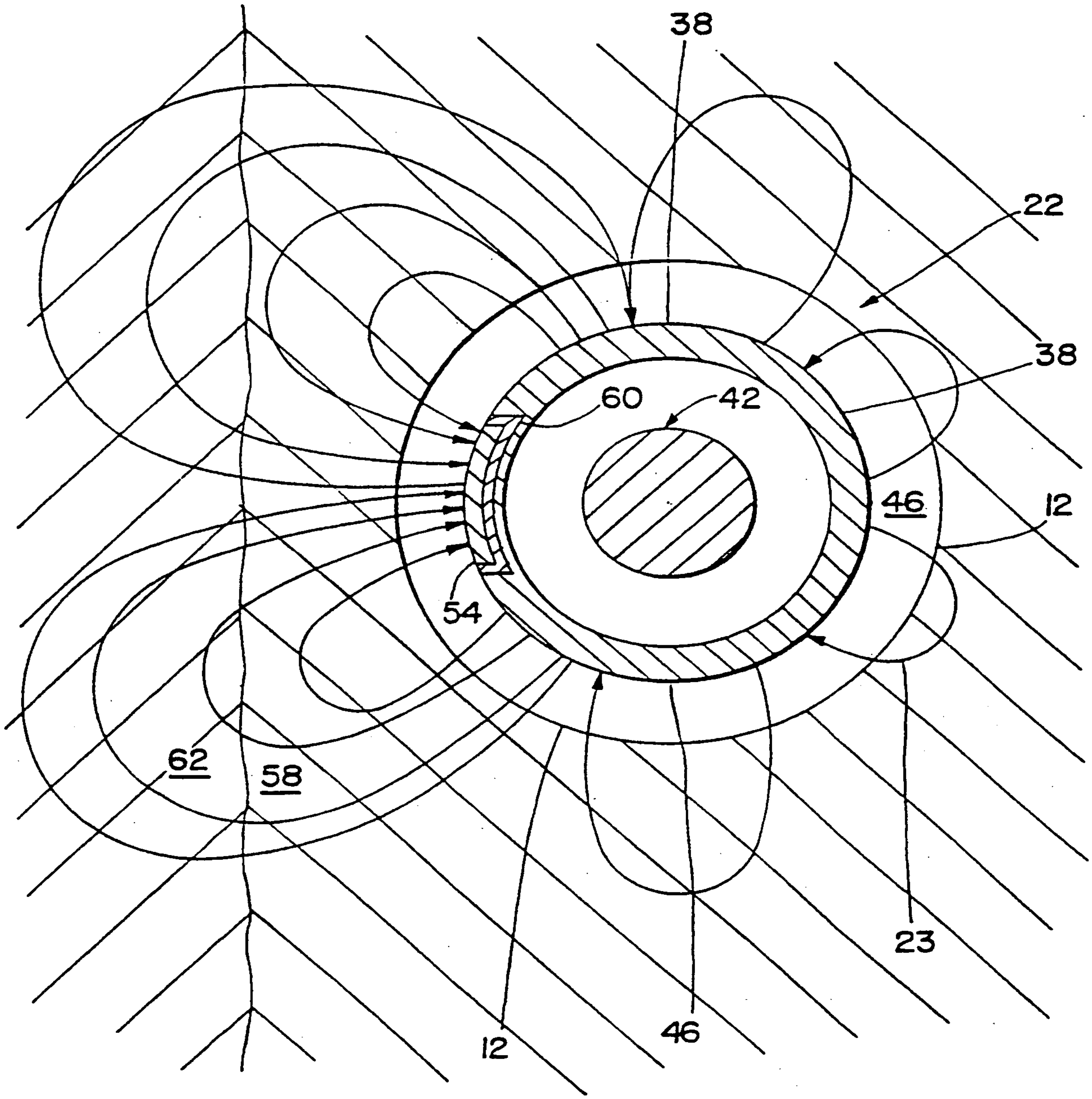


Fig. 3

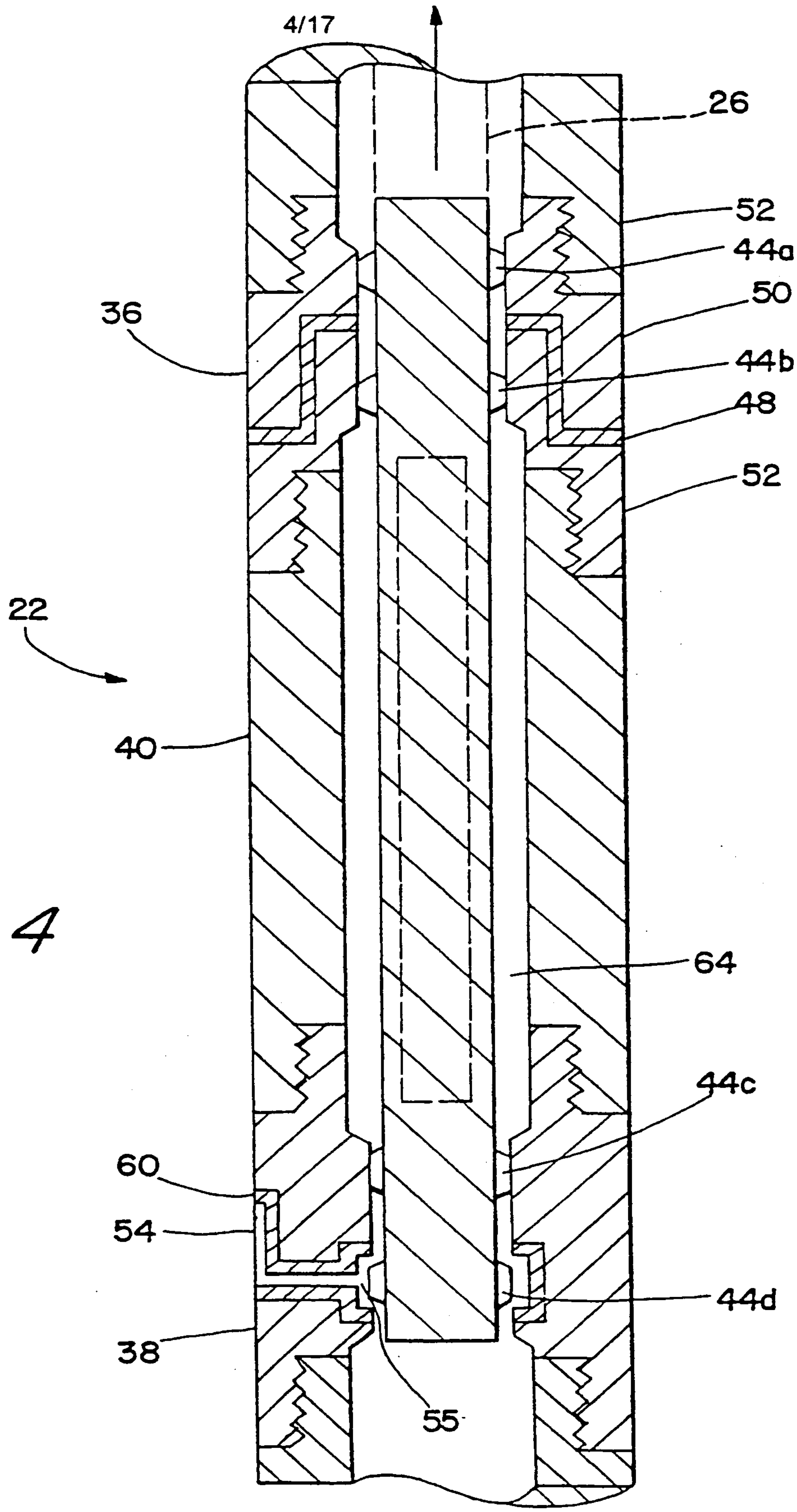


Fig. 4

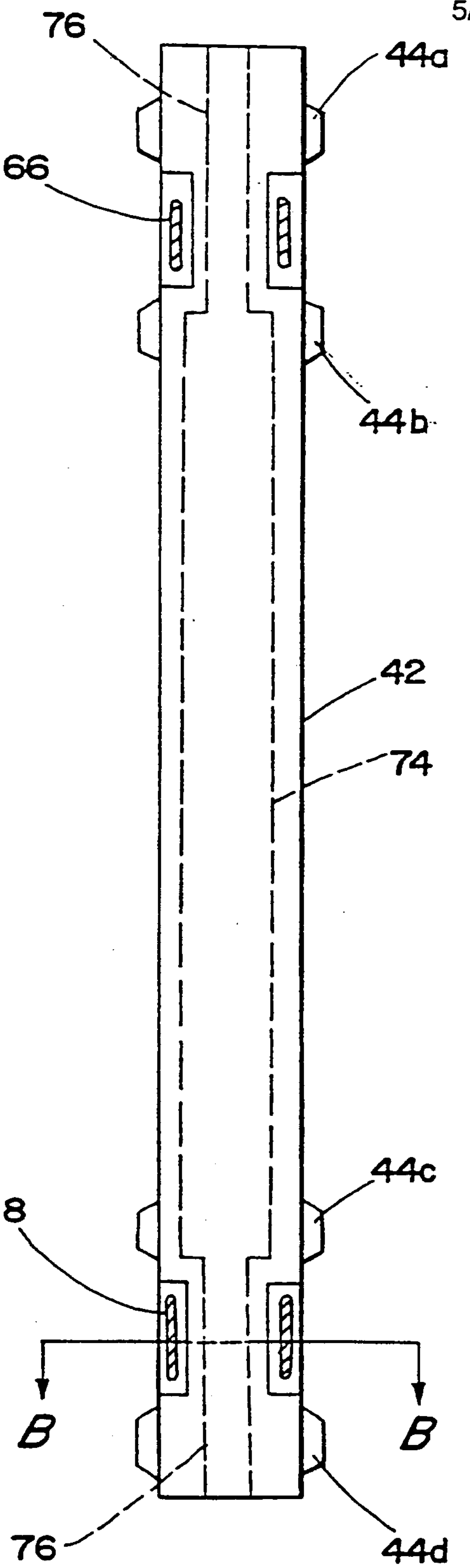


Fig. 5

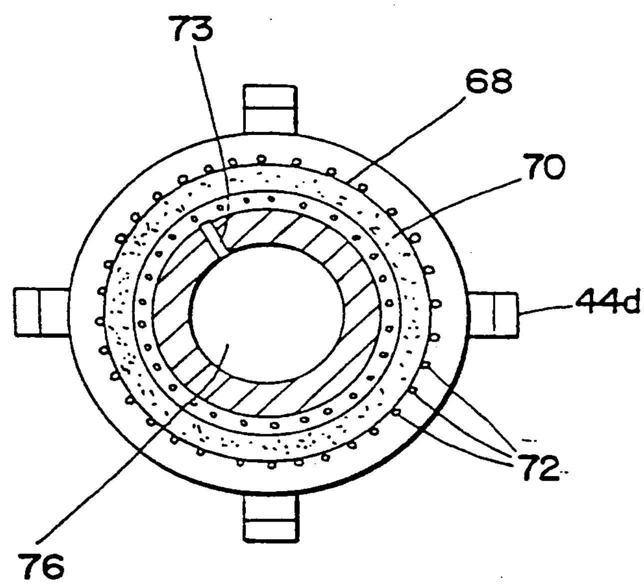


Fig. 5A

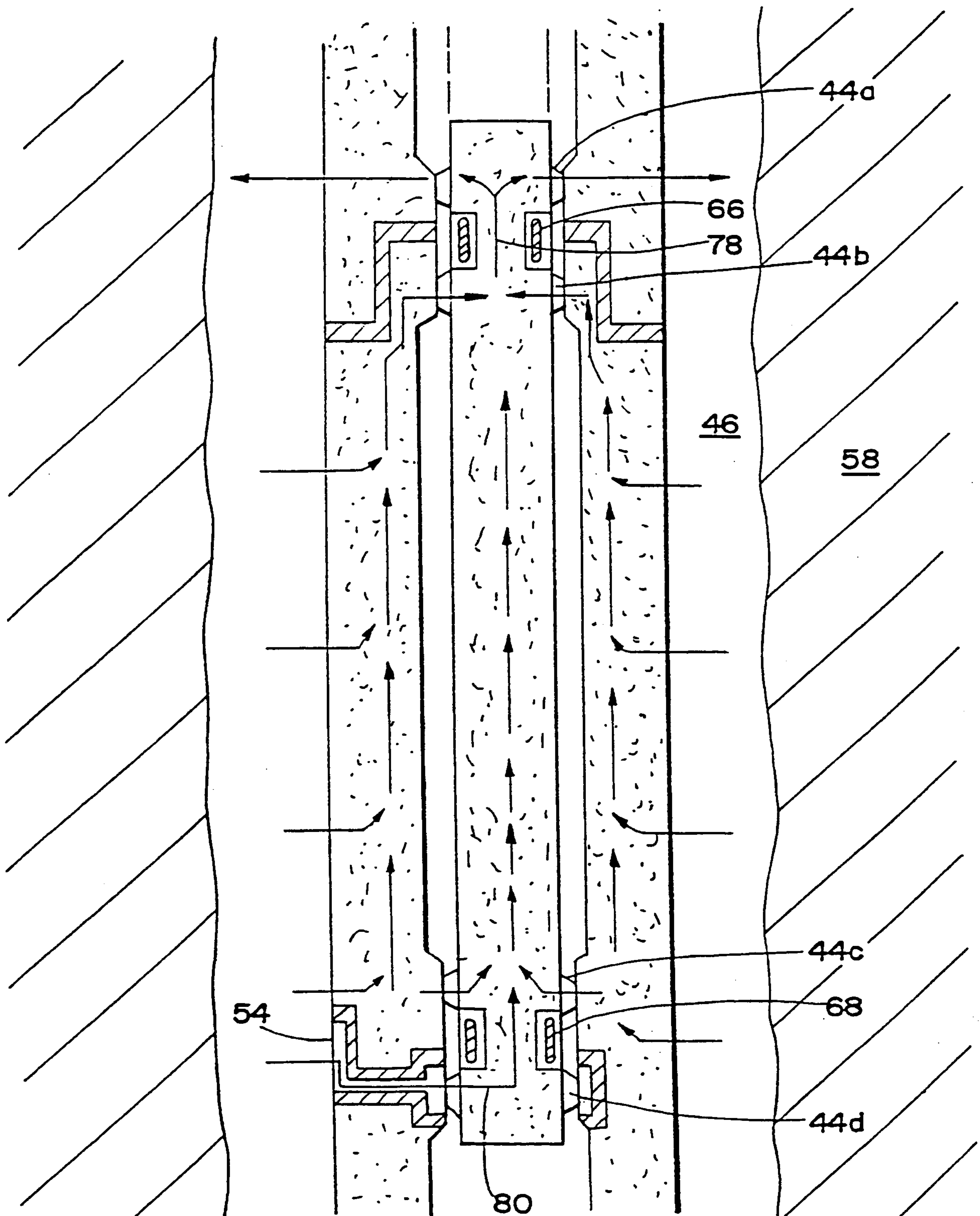


Fig 6

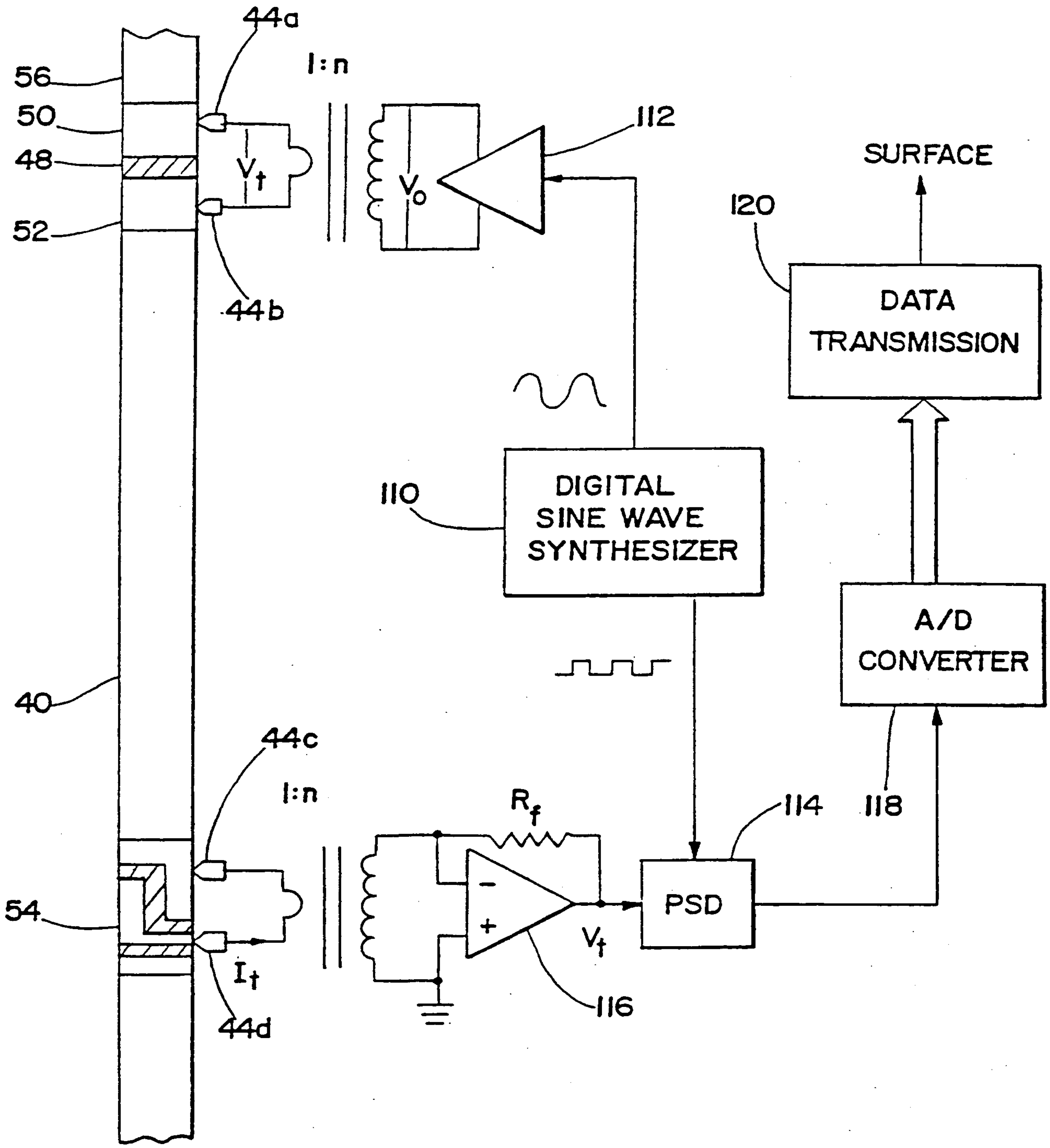

44a
1:n
56
50
48
52
44b
V_t
V_o
112
SURFACE
120
DATA TRANSMISSION
DIGITAL SINE WAVE SYNTHESIZER
110
A/D CONVERTER
40
44c
1:n
R_f
114
118
PSD
54
V_t
I_t
44d
116

Fig. 7

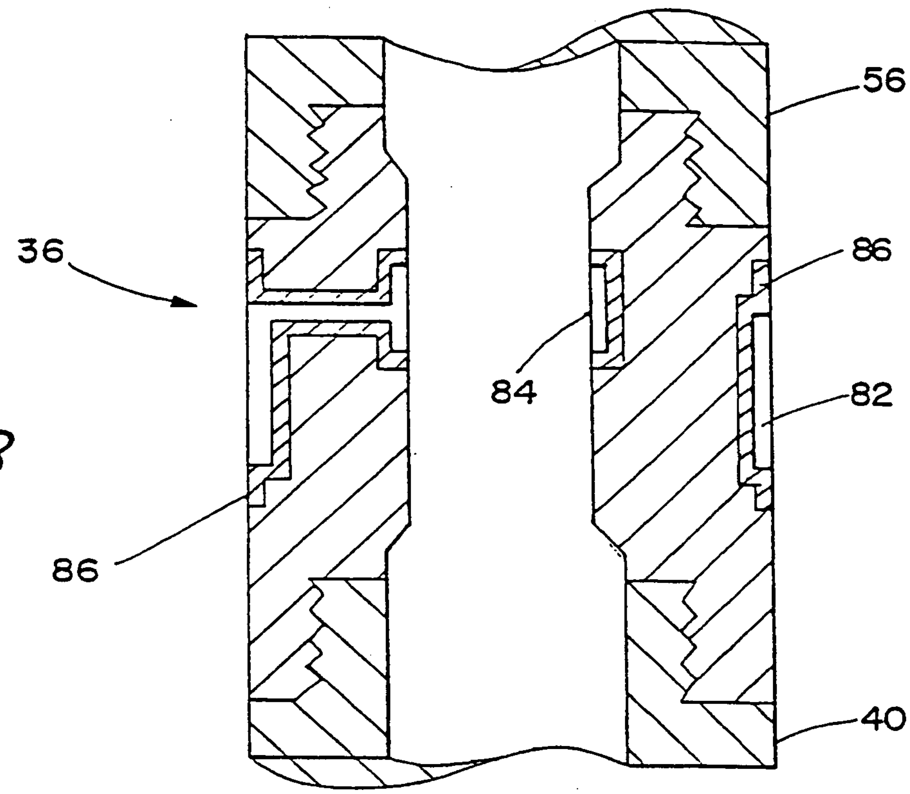


Fig. 8

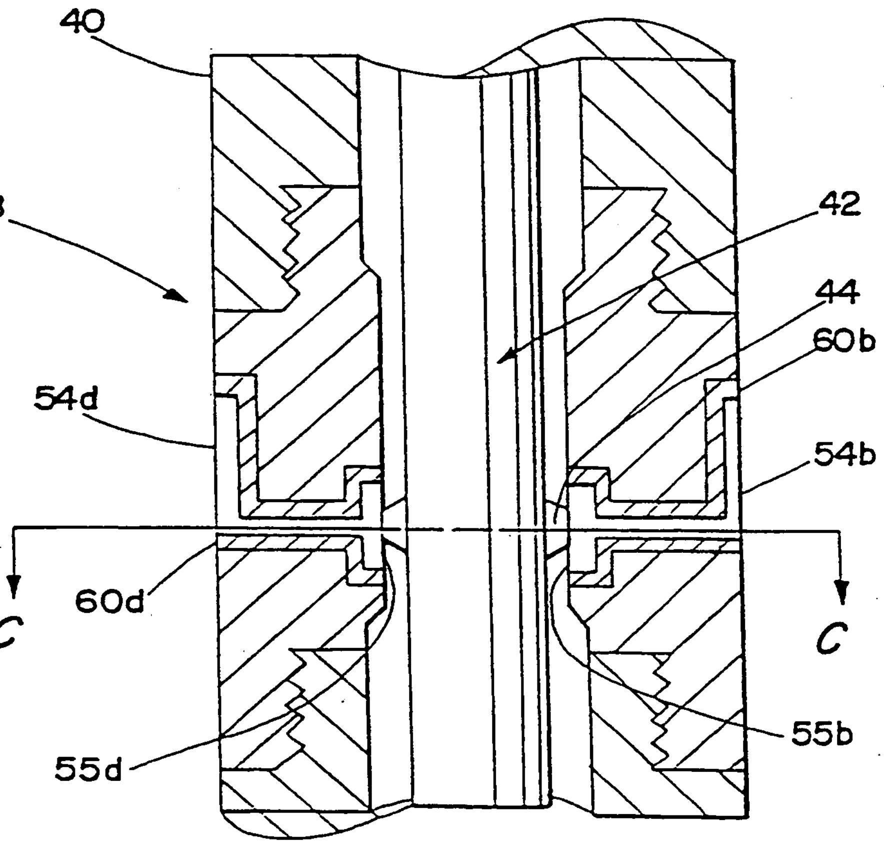


Fig. 9A

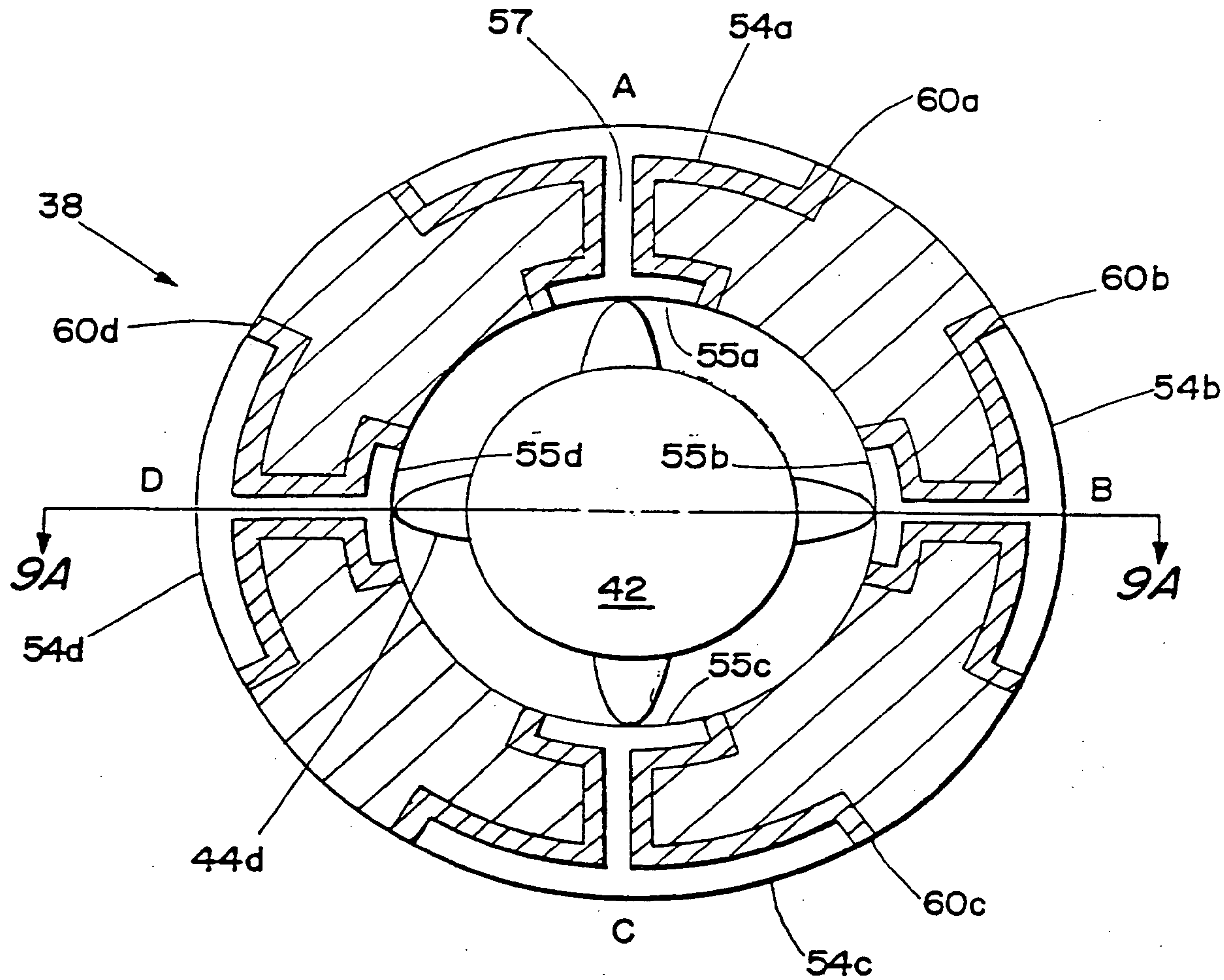

57
54a
A
60a
38
60b
60d
55a
54b
55d
55b
D
B
9A
9A
42
54d
55c
44d
60c
C
54c

Fig. 9B

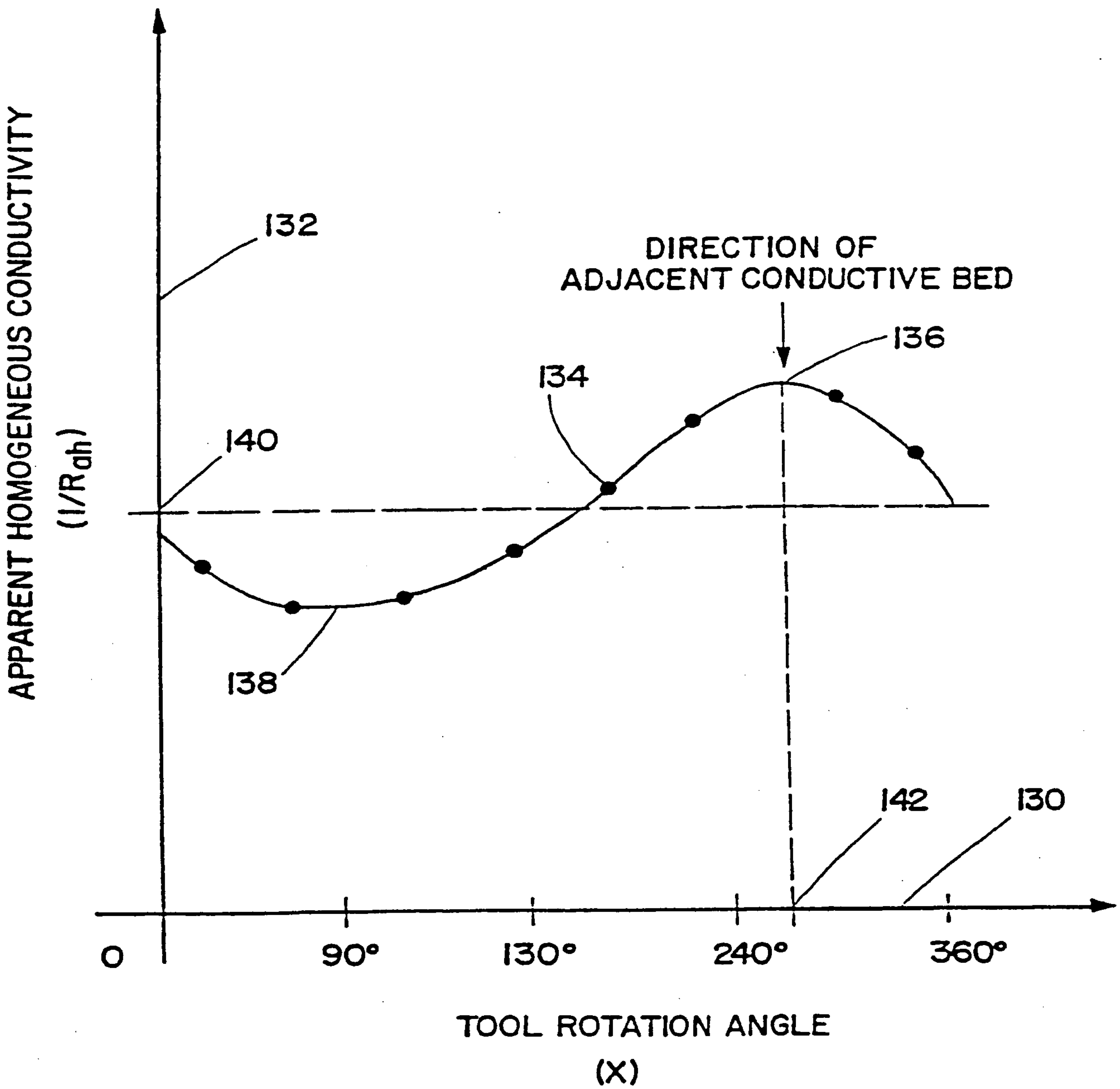

APPARENT HOMOGENEOUS CONDUCTIVITY
(1/Rah)
132
140
DIRECTION OF
ADJACENT CONDUCTIVE BED
136
134
138
142
130
0
90°
130°
240°
360°
TOOL ROTATION ANGLE
(X)

Fig. 10

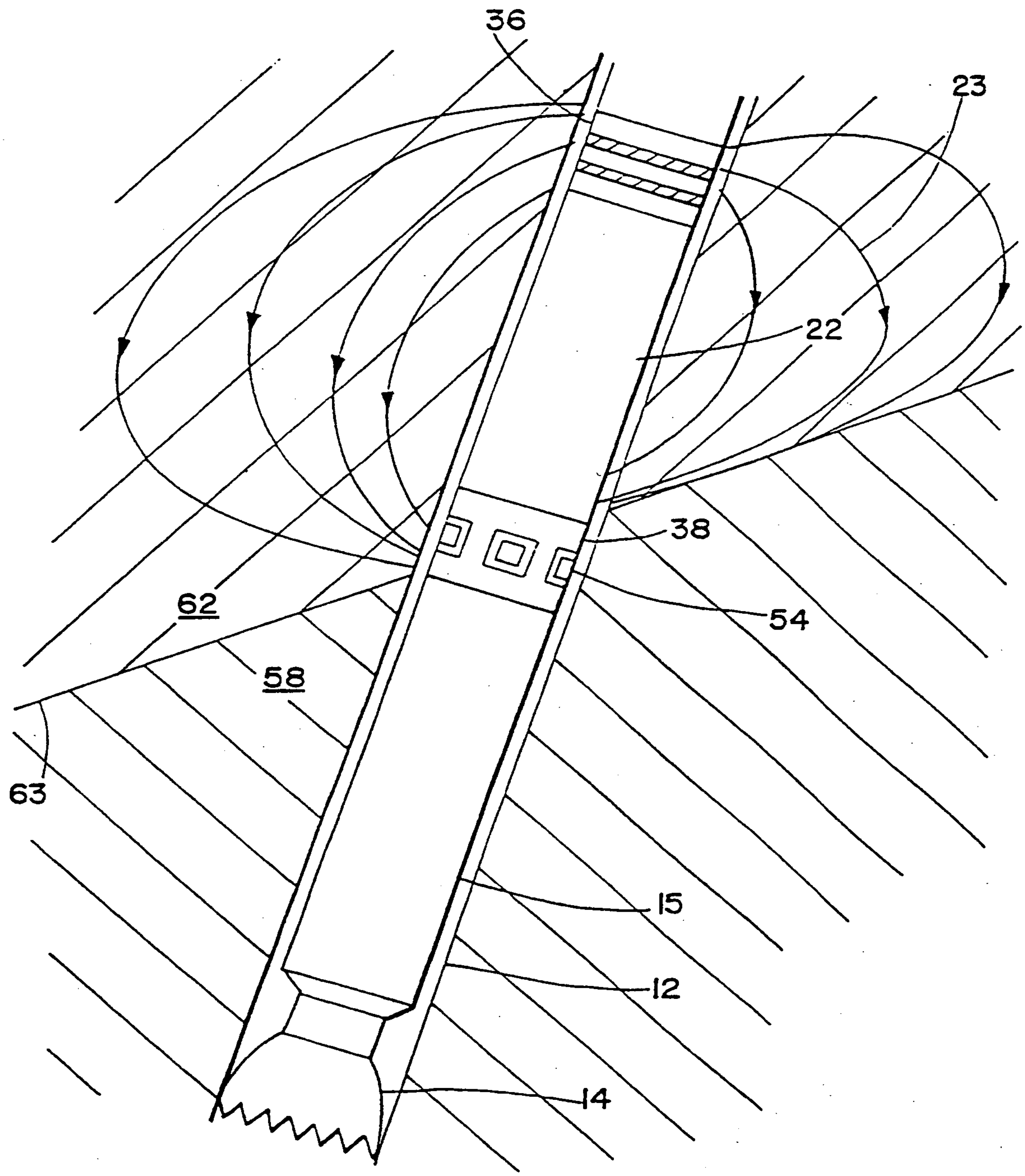


Fig. 11

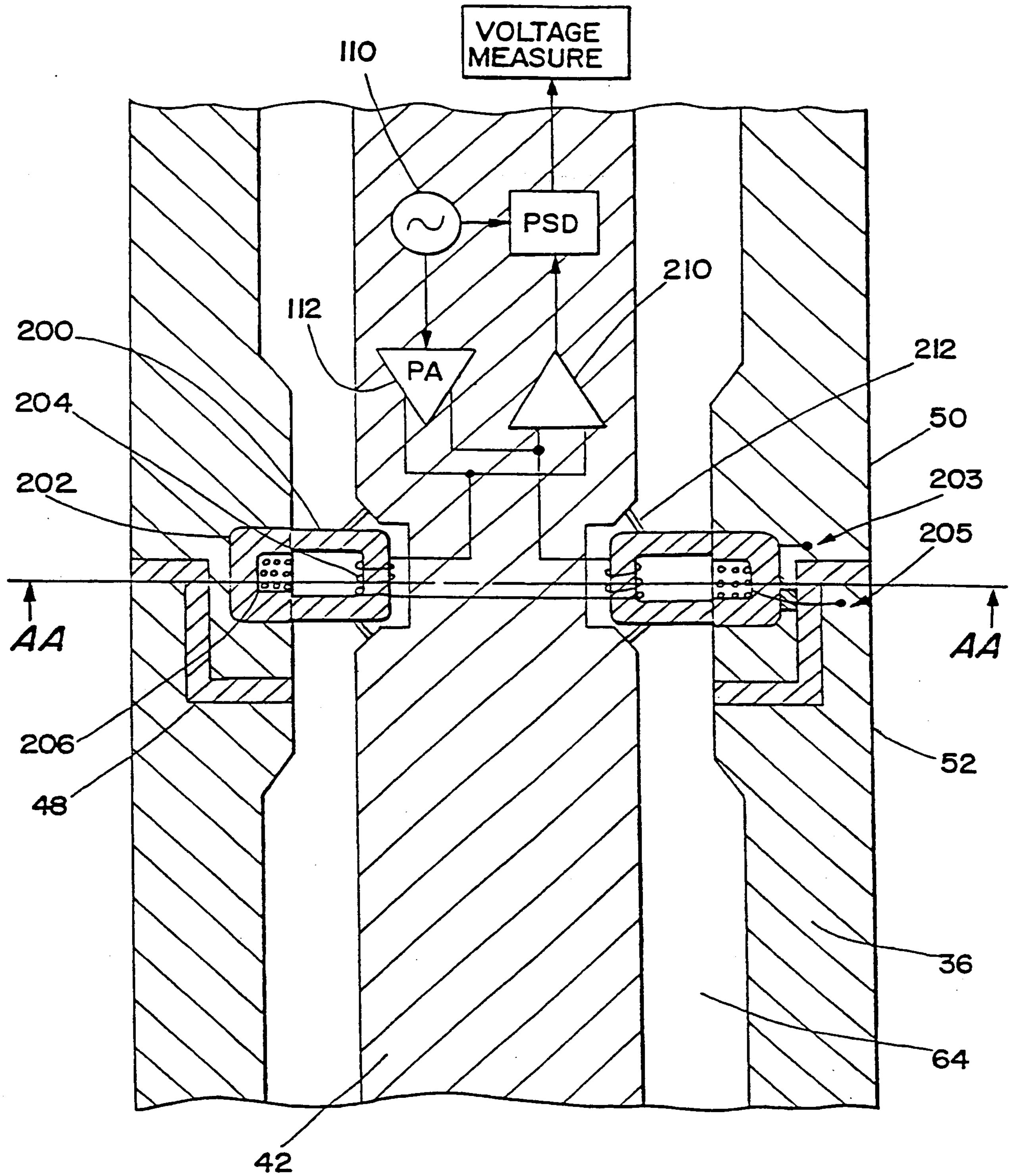

VOLTAGE
MEASURE
110
PSD
210
112
PA
200
204
202
212
50
203
205
AA
AA
206
48
52
36
64
42

Fig. 12

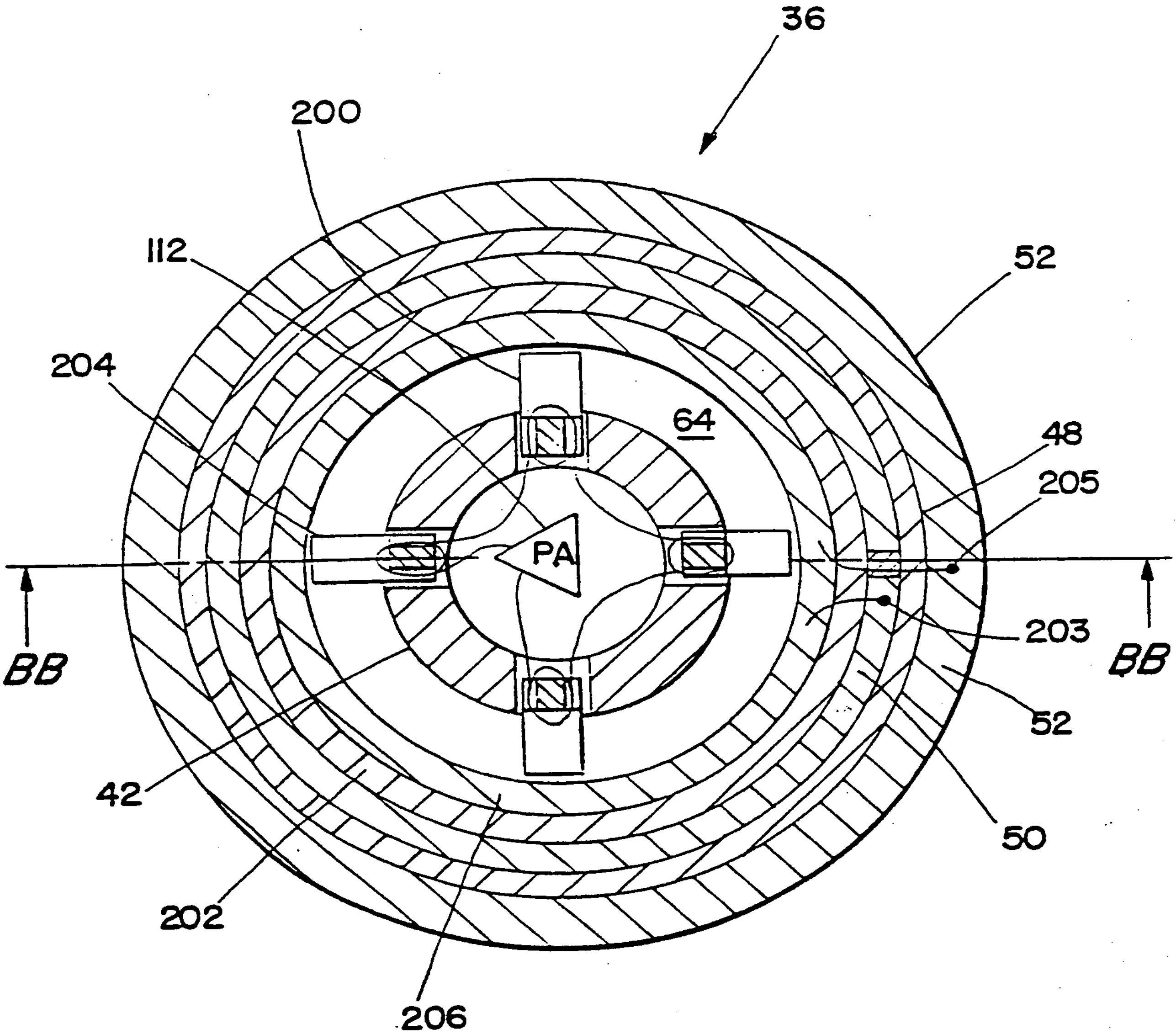


Fig. 13

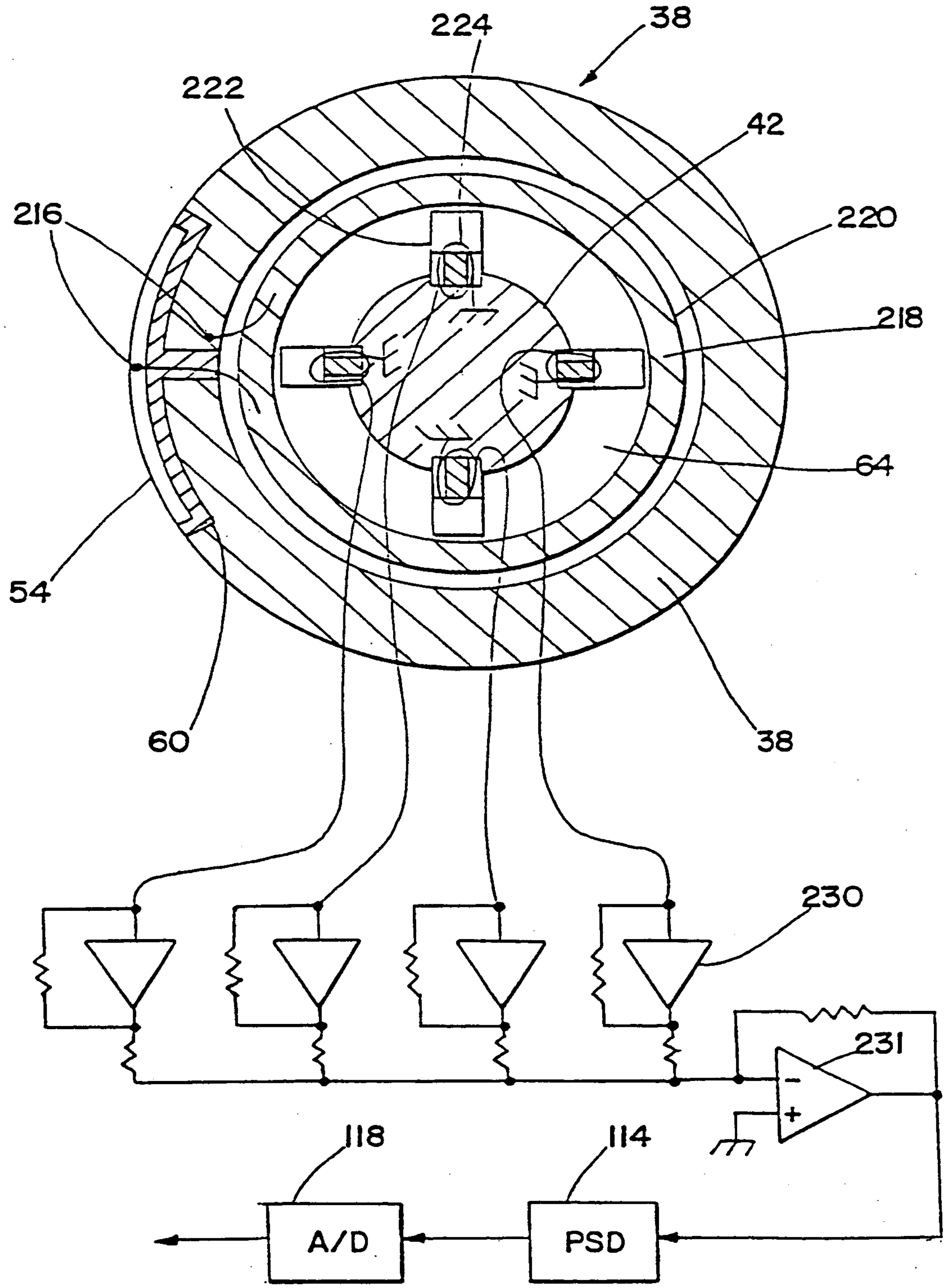


Fig. 14

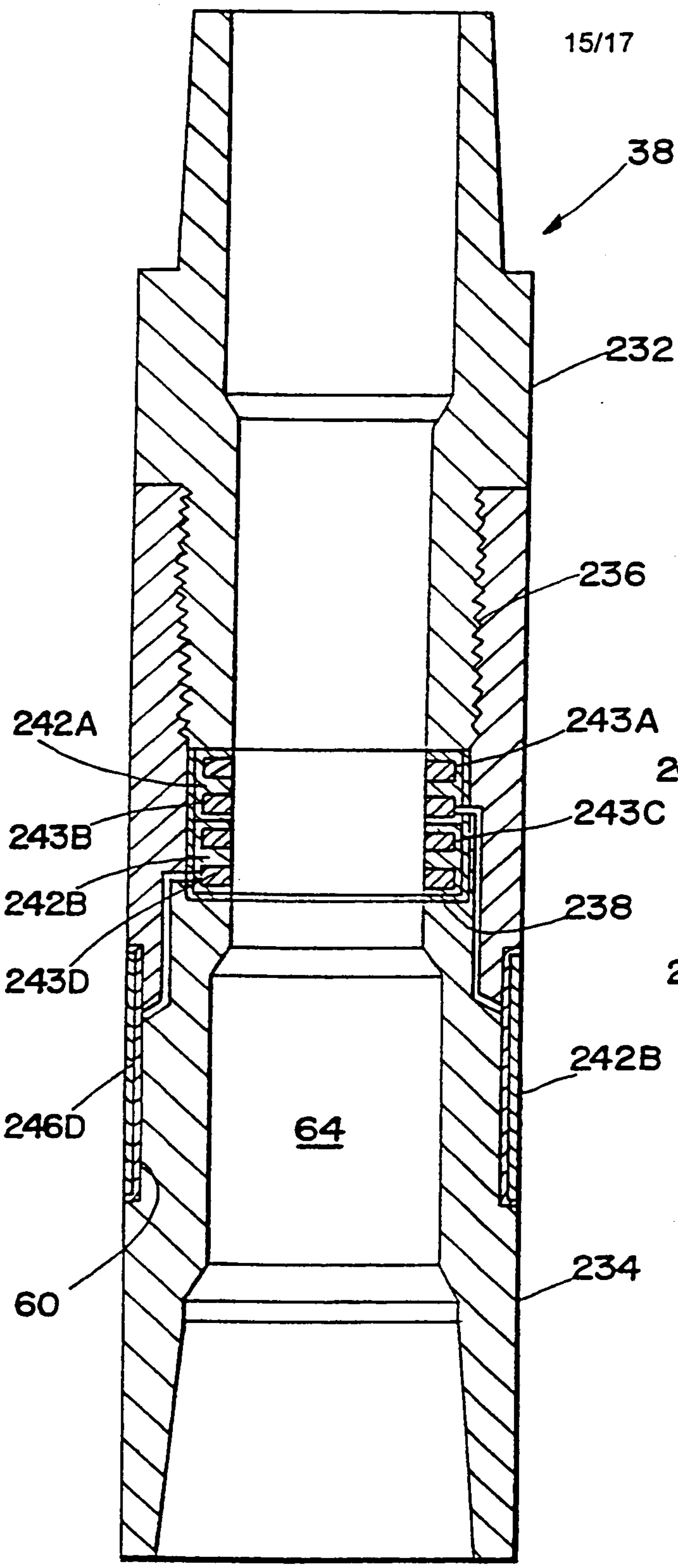
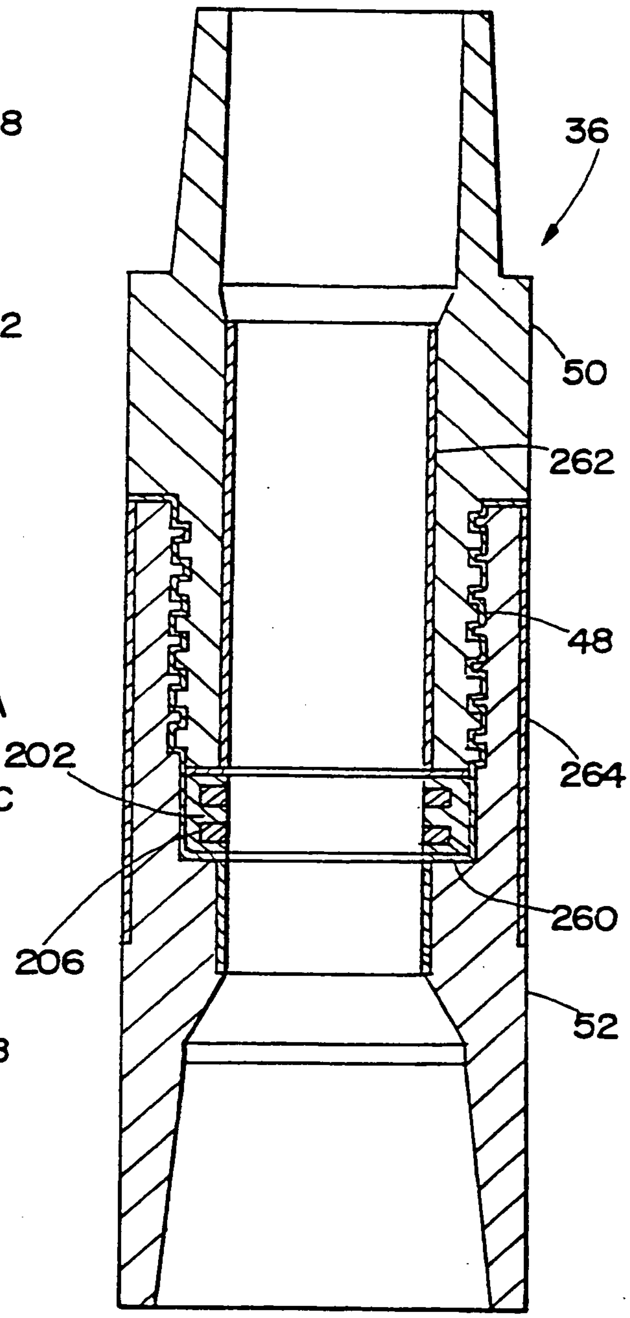

38
232
236
242A
243A
243B
243C
242B
238
243D
242B
246D
64
60
234

Fig. 15


36
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206
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Fig. 18

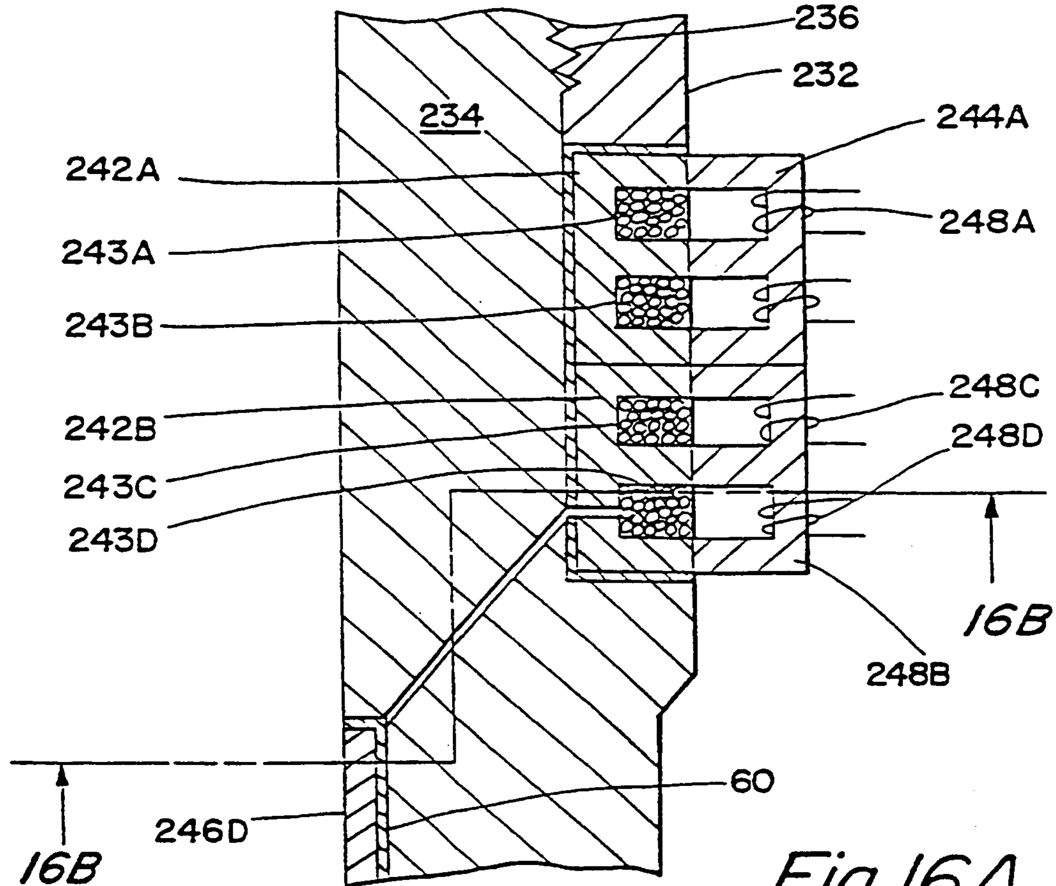

Fig. 16A

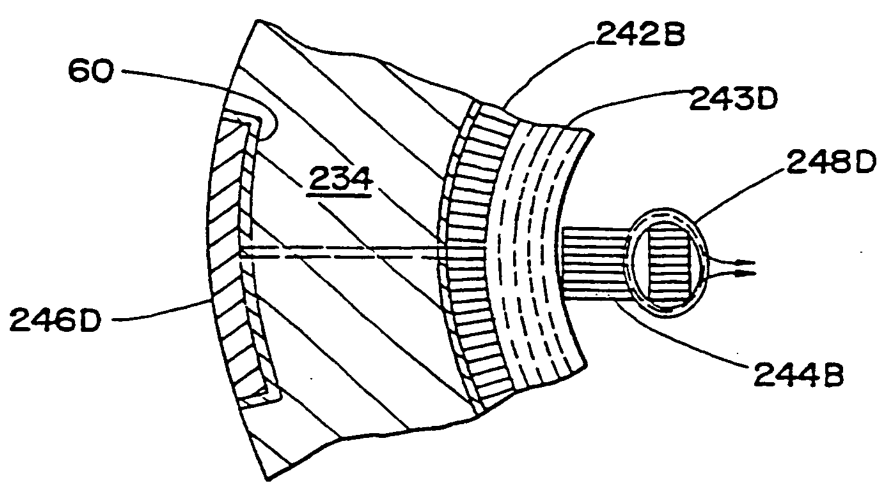

Fig. 16B

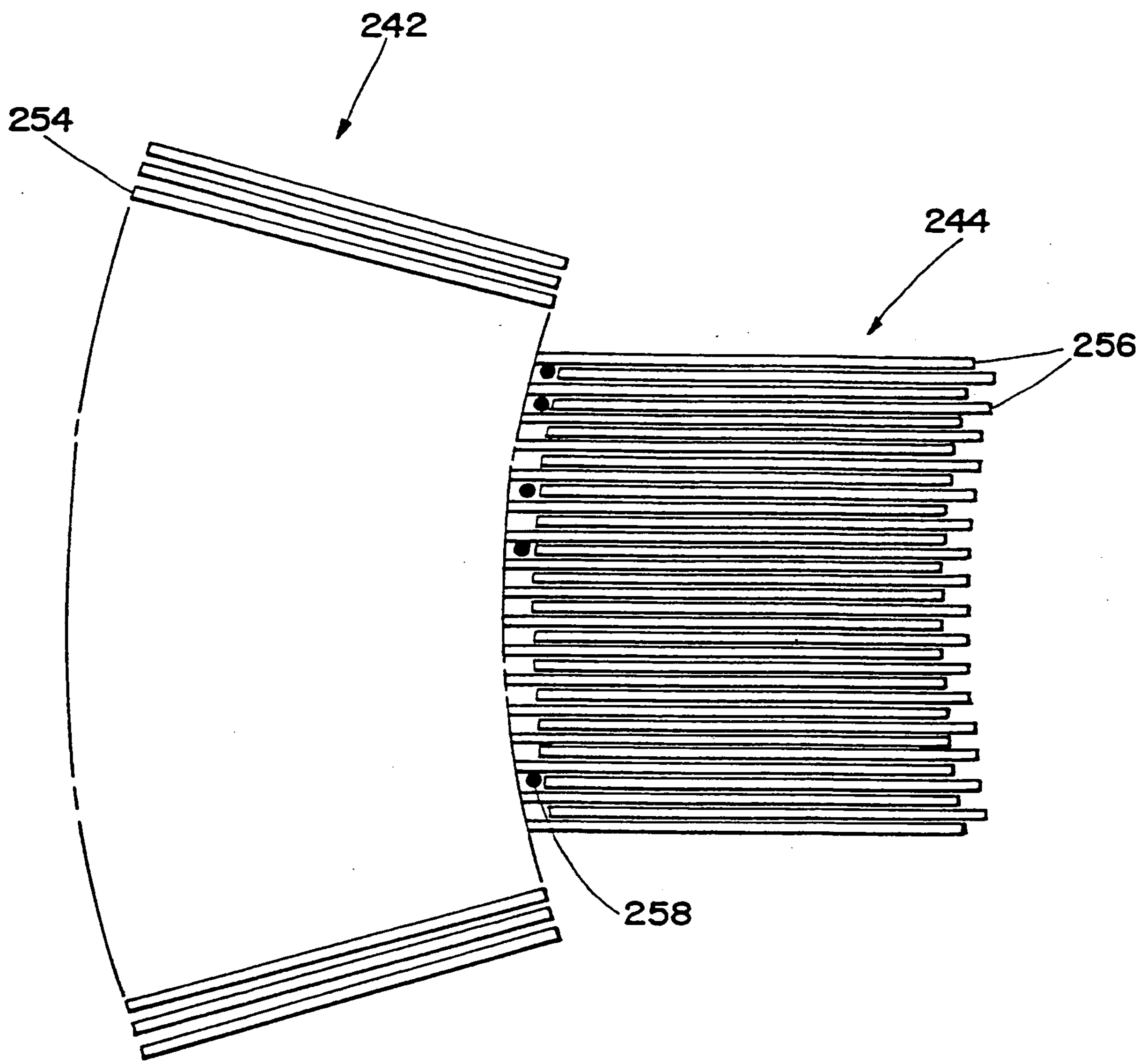

Fig. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/24296

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G01 V 3/02, 3/04
US CL :324/369
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 324/369,323,338,339,340,341,342,343,366,370,355,356

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No
Y	US 2,569,390 A (SEWELL) 25 September 1951 (25.09.51), Fig. 2	1-4,7,14-21 23-26,30- 31,36
A	US 3,293,542 A (PIETY) 20 December 1966 (20.12.66) Fig. 1	
A	US 2,650,067 A (MARTIN) 25 August 1953 (25.08.53) Fig. 1	1-53

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

09 MARCH 1999

Date of mailing of the international search report

19 MAR 1999

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